# A Methodology for Radical Innovation

## – illustrated by application to a radical Civil Engineering structure

by

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# Declaration

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Date: 26 November 2008

# Abstract

## A Methodology for Radical Innovation
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Radical, far-beyond-the-norm innovation engages unknown developmental frontiers outside the familiar fields of standardised practice, requiring new and broad perspectives. This implies significant uncertainty during problem solution – the more radical, the greater the uncertainty. No systematic procedures for managing radical innovation exist. Research managers agree that traditional, standardised innovation approaches do not provide sufficient support for managers to cope with the degree of functional uncertainty typical of radical innovations. An efficient approach for delimiting and describing its uncertainties and managing the development process during the radical innovation process is sought. This thesis synthesizes a methodology for radical innovation from Systems Engineering and Management of Technology theory. Its application in a case study illustrates how it facilitates efficient strategic decision-making during radical innovation.

Systems Engineering, by its comprehensive perspective, provides a valuable non-intuitive framework from which required radical innovation functionalities and uncertainties are identified, delimited, characterised and developed. Management of Technology concerns the core theory of technology; its perspective on technology provides the radical innovation process with a means of characterising and delimiting status, potential and uncertainty of functional, technological elements in the system.

The resulting Radical Innovation Methodology is verified through application to an emerging renewable energy concept, the Solar Chimney Power Plant, which responds to a demand for innovation aimed at sustainable energy generation. The radically tall chimney structure required by the plant, proposed to stand 1,500 meter tall, serves as a fitting case for illustrating the methodology. Addressing and solving of challenges and uncertainties related to the radically tall structure and associated costs are required toward competence of this concept in a global energy market.

# Samevatting

## `n Metodologie vir Radikale Innovasie
### – geïllustreer deur toepassing op `n radikale Siviele Ingenieurs struktuur

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Radikale, ver-buite-die-norm innovasie benader onbekende ontwikkelingsgrense wat buite die bekende velde wat gestandaardiseerde praktyk bied val; dit benodig nuwe en breë perspektiewe. Radikale innovasie gaan gepaard met toenemende onsekerheid gedurende problem-oplossing – hoe meer radikaal, hoe groter die onsekerheid. Daar bestaan geen sistematiese prosedure vir die bestuur van radikale innovasie nie. Navorsingsbestuurders stem saam dat tradisionele, gestandardiseerde innovasie-benaderings nie voldoende ondersteuning aan bestuur voorsien om die graad van tipiese funksionele onsekerhede van radikale innovasie te hanteer nie. `n Effektiewe benadering om onsekerhede af te baken en te beskryf asook om die ontwikkelingsproses tydens die radikale innovasie proses te bestuur word benodig. Hierdie tesis sintetiseer `n metodologie vir radikale innovasie vanuit stelselsingenieurswese- en tegnologiebestuurteorie. Die toepassing daarvan op `n gevallestudie illustreer hoe dit doeltreffende, strategiese besluitneming tydens radikale innovasie fasiliteer.

Stelselsingenieurswese voorsien `n waardevolle nie-intuïtiewe raamwerk deur sy omvattende perspektief vanwaar vereisde radikale innovasie funksionaliteite asook onsekerhede geïdentifiseer, afgebaken, gekarakteriseer en ontwikkel kan word. Tegnologiebestuur is bemoeid met die kern-teorie van tegnologie. Die perspektief op tegnologie voorsien tydens die proses van radikale innovasie `n wyse tot karakterisering en afbakening van tegnologiese status, potensiaal en onsekerheid van funksionele tegniese elemente in die stelsel.

Die hieropvolgende Radikale Innovasie Metodologie word geverifieer deur die toepassing daarvan op `n ontluikende hernubare energie konsep, naamlik die Sonskoorsteen Kragstasie, in antwoord op `n behoefte vir innovasie vir volhoubare energie-opwekking. Die kragstasie benodig `n radikaal hoë skoorsteen struktuur, van `n voorgestelde 1,500-meter-hoogte, wat `n gepaste geval ter illustrasie

van die metodologie bied. Adressering en oplossing van die uitdagings en onsekerhede verwant aan die radikaal-hoë struktuur en gepaardgaande kostes word benodig met die oog op bevoegdheid van die konsep in `n globale energiemark.

To Jesus Christ, thank you… for thesis blueprints, for guidance, for assistance, for back up, for space, for quietness, for friendship, for grace, for office-window views on Simonsberg sunrise and sunset, for the people along this journey. Bless them. This thesis and everything I learnt I present to You… You are the best thing that has ever happened to me.

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# General information and abbreviations

## General

A laminated bookmark is provided with the dissertation. This bookmark holds integral information conveyed throughout the dissertation and could aid the reader in following the thesis argument, development and validation. The laminated bookmark should be located in the plastic sleeve inside the back cover of the dissertation. It contains:

- summarised information on the content and flow of the document (with specific reference to chapters)
- the thesis statement and Radical Innovation Methodology diagram
- the "ideal" performance requirements for the Chimney, which may prove handy especially in the more technical chapters of Part II.

Lists of the figures and tables follow at the end of this document, after the references.

References used in the Appendices that were not referenced in the main body of the dissertation are referenced after each Appendix.

Digital versions of this dissertation with the referenced articles and calculation and modeling files are available from the author.

"He", "his", "him", "man" and "mankind" are in this dissertation used in referring to both the male and female person.

## Abbreviations

| | |
|---|---|
| - RIM | Radical Innovation Methodology |
| - SE | Systems Engineering |
| - MCDM | Multi-criteria decision-making |
| - TRIZ | Theory for Inventive Problem Solving (translated from Russian) |
| - MOT | Management of Technology |
| - STA | Strategic Technology Analysis |
| - IFR | Ideal Final Result |
| - SCPP | Solar Chimney Power Plant |

| | |
|---|---|
| - GHG | Greenhouse Gas |

| | |
|---|---|
| - US | University of Stellenbosch |
| - US-ISE | University of Stellenbosch Institute for Structural Engineering |
| - BUW | Bergische Universität Wuppertal |
| - BUW SDT | Bergische Universität Wuppertal Statik und Dynamik der Tragwerke |
| - SBP | Schlaich Bergermann und Partner Consulting Engineers |
| - SA | South Africa |

| | |
|---|---|
| - m | meter (unit of length) |
| - $m^2$ | meter square (unit of area) |
| - $m^3$ | meter cube (unit of volume) |
| - m/s | meter per second (unit of velocity) |
| - rad/s | radians per second (unit of angular velocity) |
| - $m/s^2$ | meter per second square (unit of acceleration) |
| - $kg/m^3$ | kilogram per cubic meter (unit of density) |
| - N.m | Newton meter (unit of a structural moment) |
| - Pa | Pascal (unit of pressure in Newton per meter square), Giga-Pascal (GPa) being one thousand million Pascal. |
| - Hz | Hertz (unit of frequency measured in revolutions per second) |
| - MW | megawatt (unit of power of one million watts) |
| - kWh | kilowatt-hour (unit of work done by a power of one thousand watts for one hour) |
| - GWh/y | gigawatt-hour per year (unit of work done by a power of one thousand million watts for one hour over the duration of a year) |
| - LEC | levelised electricity cost (investment, operations and maintenance cost per kilowatt-hour of electricity produced over the project lifetime) |
| - R | Rand (South African monetary unit) |
| - $ | Dollar (United States of America monetary unit) |
| - Bn | Billion (a thousand million) |
| - Mn | Million |

# CHAPTER 1

# INTRODUCTION

Mankind is surrounded by problems – sources of difficulty that challenge the standards and liberties that he values. Problems need resolution to ensure man's survival, safety, health and security; successfully resolving a problem earns man these securities. *If* he can overcome it in a revolutionary or breakthrough – in a *radical* – way his greater success earns him favour over competitors, challenges and problems.

A radical striving "far beyond the norm" [Webster 2008] characteristically engages unknown frontiers and new sets of values, standards and perspectives, implying increased uncertainty[i] – the more radical, the greater the uncertainty – and unpredictable progress during problem solution. This thesis investigates the systematising of radical innovation to understand and manage its uncertainties, leading to more efficient innovation.

## 1.1 Introducing radical innovation

### 1.1.1 Innovation and radical innovation defined

Due to equal competence of companies in the management of operations, human resources, marketing and strategy, corporate focus recently shifted to the key to their competitive advantage: innovation [Harrison and Samson 2002]. An *innovation* presents a solution to a problem by realising a product from its creative invention all the way to market inception [Stefik and Stefik 2004].

While *incremental* innovation involves the exploitation of existing functional, parametrically-defined capabilities within the context of a familiar field, *radical*[ii] innovation "changes the game" by providing significantly more favourable functional definition that

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[i] Uncertainty, in this thesis, refers to the undefined, qualified *or* quantified probability of achieving a preferred outcome.

[ii] Several texts investigate characteristics of *disruptive* (relative to the current market state) technologies. Disruptive technologies are characterised by high innovation uncertainties, with potential transforming change of the product/market economy. *Sustaining* technologies support competitive advantage through relative, incremental developments with the aim of enlarging market share. Explanatory texts include Walsh [2004] and Kostoff et al. [2004].

*transforms* the existing technological and product feature range, customer–supplier relationships and marketplace economies [Harrison and Samson 2002, Leiffer et al. 2000]. Table 1-1 provides a comparison between the characteristics and terms typically encountered in incremental and radical innovation.

Table 1-1. Characteristics of incremental and radical innovation.

| **Incremental innovation** | **Radical innovation** |
|---|---|
| Exploit the existing | Explore the potential |
| Familiar field, smaller uncertainties | Unfamiliar field, significant uncertainties |
| Parametrically defined | Functionally defined |
| Novel implementation of codified/standard practice | Absence of codified/standard practice |
| Dramatic results | Transforming results |
| Clear terms, goals, business plan, financial projection, funding | Uncertain terms, sporadic project termination/revival, change of priorities/champions, multi-disciplinary, multi-criteria uncertainty |
| Goal: product | Goal: diminish uncertainties to justify further investment |

In some cases, the impact of incremental innovation may appear dramatic being characterised by novel implementation of codified design practice through interpretation and manipulation from scientific first principles, thus achieving dramatically improved designs within a specific, familiar field. A distinction is made, however, between dramatic incremental innovation and radical innovation. Radical innovation is required in the *absence* of sufficient codified design practice at one or more lower levels in a system. Therefore, it requires innovation *outside* the familiar realms of standardised, formalised theory and practice by identifying, re-interpreting and addressing the basic system functionality that requires solution. With radical innovation a major breakthrough in one or more governing parameters is sought in an exploring manner through extensive familiarisation with the root of the problem in a possibly unknown context. Cross-disciplinary perspectives often need to be introduced in order to identify and characterise these roots and sources of uncertainty in the radical problem [Stefik and Stefik 2004]. As technological capability is progressively acquired and developed, the limiting factors and uncertainties diminish to a point of acceptability with regard to general engineering practice. This definition of radical innovation is central to the development of the subject of this thesis.

Examples of historical radical innovations are the use of steam to propel ships hereby substituting sails, turbines substituting piston engines to generate power, the substitution of vacuum tubes with transistors, the Internet and the Apollo Space Project, each disrupting normative technological standards [Christensen and Bower 1996] by introducing revolutionary performance standards.

Pure radical and incremental innovation are considered to be extremes, incremental innovation being the case where the radical characteristics of the innovation are diminished to a state of manageability by standardised design methods.

### 1.1.2 Difficulties in managing radical innovation

Although executives of established companies acknowledge that radical innovation is critical in providing them with long-term renewal and growth, their successful development and deployment of radical innovations remain unpredictable and fuzzy [Leiffer et al. 2000]. In contrast to incremental innovation, which is characterised by short-term, clearly defined, parametrical processes with committed funding and development teams, radical innovation is characterised by high degrees of multi-disciplinary and multi-level technical, market, resource and organisational uncertainty and unpredictability. Its time frames are long-term with sporadic project terminations and revivals, nonlinear recycling of the response to previous setbacks and stochastic change of priorities and champions, thereby creating a mix of accelerating and retarding factors [Leiffer et al. 2000].

The all encompassing goals of the radical innovation project are to overcome project discontinuities and progressively reduce the non-empirical, non-intuitive uncertainties through their sufficient characterisation in order to attract investors for the next phase of the innovation life cycle. This cannot be achieved by mere parameterised design and relevant organisational support, which is the subject of incremental innovation. The reduction of uncertainty is not predictably progressive or sequential; its degree may fluctuate throughout the project.

Due to the lack of understanding of the processes through which radical innovation emerges, executives either choose to disengage radical innovation or make autocratic strategy decisions based on knowledge of mainstream business, expecting to see specific project goals, early market research results and detailed financial projections. Alternatively they settle as “fast followers” of radical concepts rather than actively manage its innovation [Leiffer et al. 2000]. *The need for a systematic approach to managing the uncertainties in radical innovation is evident.*

## 1.2 Thesis statement: a methodology for radical innovation

Radical innovation can be better managed and its behaviour more surely predicted, the more thorough its uncertainties are delimited and characterised. Adequate competencies to identify and track these uncertainties are crucial. The thesis statement is formulated: *Radical innovation can be systematised through the synthesis of existing theory to form a basis for strategic decision-making.*

Two scientific fields, Systems Engineering and Management of Technology, are engaged for its potential contribution to the synthesis of a systematic approach aiding radical innovation.

Systems Engineering (SE) involves interdisciplinary technical effort to transform a requirement into a synthesised solution of subsystems and components [(based on) INCOSE 1998]. SE, by its comprehensive nature, could provide valuable insight into the required radical innovation functionalities resulting in a systematic, non-intuitive framework within which uncertainties and deficiencies can be identified, delimited, characterised and developed.

*Technology* is a widely abused term summoning images of high-tech gadgets or only perceived as the “grey mist floating” behind a company’s[iii] product portfolio [Ford and Saren 1996]. Broadly defined, it is the mechanism through which mankind leverage its efforts to improve its quality of life [Harrison and Samson 2002]. Its scientific comprehension could unlock insight into the building blocks of engineering endeavour. Management of Technology (MOT) concerns the core theory of technology and its dynamics, innovation, project management and policy in an ethical, environmental, economical and political context [Van Wyk 2004a, Steele 1989]. Its perspective on addressing functionality and managing technological

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[iii] Although Management of Technology (MOT) generally applies with reference to a *company* (due to the relevance of MOT for managing the unit of an engineering company’s enterprise – technology), this dissertation uses “company” only to the extent that it is a facility implementing MOT; the principles and methods proposed in this dissertation apply to the generic facility requiring radical innovation. In a similar fashion the term “board” or “board of a company”, throughout this dissertation, refers to the final decision making authority of the company or facility implementing MOT.

potential could provide the radical innovation process with a means of characterising and delimiting status, potential and uncertainty of system elements.

## 1.3 Motivation

### 1.3.1 A systematic approach for the management of radical innovations

Several texts focus on the subject of radical innovation, gaining insight from characteristics, challenges and strategies perceived in several radical innovation case studies [Grulke 2001, Stefik and Stefik 2004, Leiffer et al. 2000] or addressing organisational competencies required to cultivate radical innovation [Leiffer et al. 2000]. No systematic approach, tying together these fragmented insights and tools in order to address the radical problem, is presented. Technology roadmaps for managing the identification and/or development of disruptive technologies (refer to Footnote *ii* in Section 1.1.1) were compiled [Gerdsri and Kocaoglu 2003, Vojak and Chambers 2004, Walsh 2004, Kostoff et al. 2004] and draw mainly on business, managerial and MOT insights to formulate perspectives and methodologies to identify and develop or manage against potentially disruptive technologies.

The only resources toward managing the erratic, uncertain characteristics of radical innovation (stated in Section 1.1.2) are commercially driven or vague and fragmented approaches to solving the radical problem. Their systematising could improve the management of radical innovation through the quantification of uncertainty, resulting in a higher success rate in realising radical innovations.

Extending project management to radical innovation management

Global competition over the past decades drove firms to compile a comprehensive incremental innovation project management knowledge base whereby systematic management tools enable project teams to move complex innovation along efficiently. On this basis, firms have become adept at continual improvement, operating on the premise that future results can be predicted through experiential trends with uncertainty being the exception on a well-defined development path. This body of knowledge is not adequate for the management of the degrees of multi-level uncertainty encountered in radical innovation [Leiffer et al. 2000]. No method systematically addressing the technical challenges associated with radical innovation exists. In order to radically innovate, new approaches and tools must redefine the traditional project management toolbox.

Synthesis of SE and MOT approaches

Comprehensive radical innovation processes presumably exist in the mind-and-method of technology management experts. Formalised theory, however, only contains *elements* toward a common radical innovation methodology. SE offers systems breakdown and analysis methods to identify gaps in the radical innovation system. MOT provides technology assessment, trend identification and strategy formulation.

SE system innovation engages radical innovation with reluctance because uncertainties at subsystem levels perpetuate to unmanageable uncertainty at higher system levels. Sherwin and Isenson [1966], when investigating the role of technological innovation in the successful acquisition of weapon systems for the United States military, supports this assertion when observing that project failure is almost imminent when lower level technologies are still developed during synthesis of a higher level system.

Standardised practice for synthesis at upper systems levels is not geared to accommodate the uncertainties perpetuating from lower levels, thus the definition of radical innovation (Section 1.1.1) as innovation focussing on basic functionality, operating *outside* familiar practice. Mitigation of uncertainties through addressing these lower levels in the system calls for the identification and addressing of the required functionality or technology – mere novel interpretation of standard practice will not suffice. The field of MOT is concerned with the management of these functionalities or technologies. A focussed attempt to direct the many strategic approaches and tools of MOT to be applied in the management of the development of the sought technologies, may reduce uncertainty to more manageable proportions.

Further, although detailed knowledge is limited at early, conceptual phases of the innovation life cycle, important decisions typically committing up to 75% (based on standardised, non-radical SE theory) of projected total life-cycle cost must be made with changes during later life cycle phases having adverse implications on project cost [Blanchard and Fabrycky 2006].

This thesis proposes a synthesis of SE and MOT theories into a generic systematic radical innovation methodology. It proposes the furtherance of SE, aiming to manage the radical innovation problem identified by Sherwin (high uncertainty in user systems due to perpetuated lower level uncertainty), by extending high level system performance measurement and strategy formulation to incorporate quantitative low-level technological evaluation, assessment and research and development (R&D). This is achieved through the application of MOT methods during the decision-making process.

### 1.3.2 Technological insight into radical innovation decision-making

The quantification of the impact of technological improvements on multi-disciplinary criteria (in order to make informed decisions) remains a complex task for the technology manager. By adhering to a technology-based perspective, the decision-maker gains insight into the characteristics of the systems that form the company products, and into the maturity of these units with consequent identification of uncertainties, improvement potential, trends and barriers. The vessels – technologies – harnessing overall system advance are thus understood more thoroughly. In this way the technology manager is equipped to vouch for the development progress, direction and deadlines enabling rational radical innovation decision-making at an executive level. Although boardroom decisions on radical innovation are generally made on the grounds of strategic business sense, the proximity of the technological insight enables decision-making based on the status of technological elements of the company product portfolio.

### 1.3.3 Sustainable technological innovation

The almost unrestrained rise of technological enterprise in the 20th century had an immense – and largely unsustainable – impact on the social, economical and ecological environment [Stern 2006]. Consumerist values justified this short-term rise in the name of progress and achievement of market share. While, from an economic and marketing perspective, these endeavours were very successful, they are catastrophic failures when viewed in a broader, sustainable context [Van Wyk 2004b, Stegall 2006], for instance where health and environmental interaction is concerned [Ford and Saren 1996]. Post-millennial man is now faced with the task of taking responsibility for these catastrophic impacts, cultivating a long-term perspective in an attitude of custodianship [Stefik and Stefik 2004].

The solution lies with harnessing technological power and impact by a sustainable approach. In order for technology to be managed efficiently, engineering perspective should widen to view companies and projects as socio-technical systems, responsive to the broader environment [Harrison and Samson 2002]. The containment process may require radical technological intervention in several spheres of society, economy and ecology, demanding the fast-tracking of radical technological solutions for circumvention of the numerous global crises, such as adverse climate change, water scarcity, sanitation, malnutrition, famine and energy requirements, to name a few [Lomborg 2005]. Procedures that could guide this radical innovation, proposed by this thesis, *are* emerging with the rise of sustainability and systems sciences, providing holistic approaches toward sustainable solutions.

### 1.3.4 The Solar Chimney Power Plant

The methodology developed for this thesis responds to a demand that is representative of the great need for sustainable solutions: that of the development of the Solar Chimney Power Plant (SCPP), and more specifically its 1,500 meter tall chimney structure, until feasibility is proven. The second part of this dissertation focuses on the application of the developed methodology on the radical innovation of this chimney; hence, a brief summary of its context, principle of operation and challenges is appropriate to illustrate its contribution to motivation for this research.

When engaging the subject of the SCPP one is struck not only by conceptual simplicity and a hope for a sustainable solution through emission free energy generation that is not dependant on water availability, but also by the sheer reality of the challenges of realising a chimney structure of more than twice the height (proposed) of the tallest structures in the world.

A SCPP, illustrated in Figure 1-1, consists of a transparent circular solar collector supported relatively low above the ground surface and a tall chimney central to the collector. Turbo-generators are located at its base. Solar radiation penetrates the collector roof and heats the ground beneath, which in turn heats the adjacent air causing it to rise through the chimney, driving the turbine and consequently generating electricity [Pretorius et al. 2004].

An economy of scale applies to the SCPP; the energy output of the power plant increases exponentially with increase in collector and chimney size. A 1,500 meter tall chimney yields almost three times more energy annually than a 750 meter tall chimney [Schlaich 1995], forming the basis for insistence from proponents of the SCPP technology in Southern Africa for the immediate realisation of a 1,500 meter structure [Stinnes 2004]. Realisation of this structure holds a key to the market feasibility of the SCPP but the challenges and uncertainties presented by its structural and economic realisation qualify it as a radical innovation, sufficient to serve as a case for illustrating the validity of the methodology proposed in this thesis. The need for a technology development strategy to scale from known science to the unknown realm of this envisaged mega-structure – its radical innovation – is evident.

## 1.4 Thesis deliverables

A systemised, methodological approach to managing radical innovation is presented.

A secondary objective comprises the set up of an innovation strategy for improvement of the performance of the SCPP chimney structure.

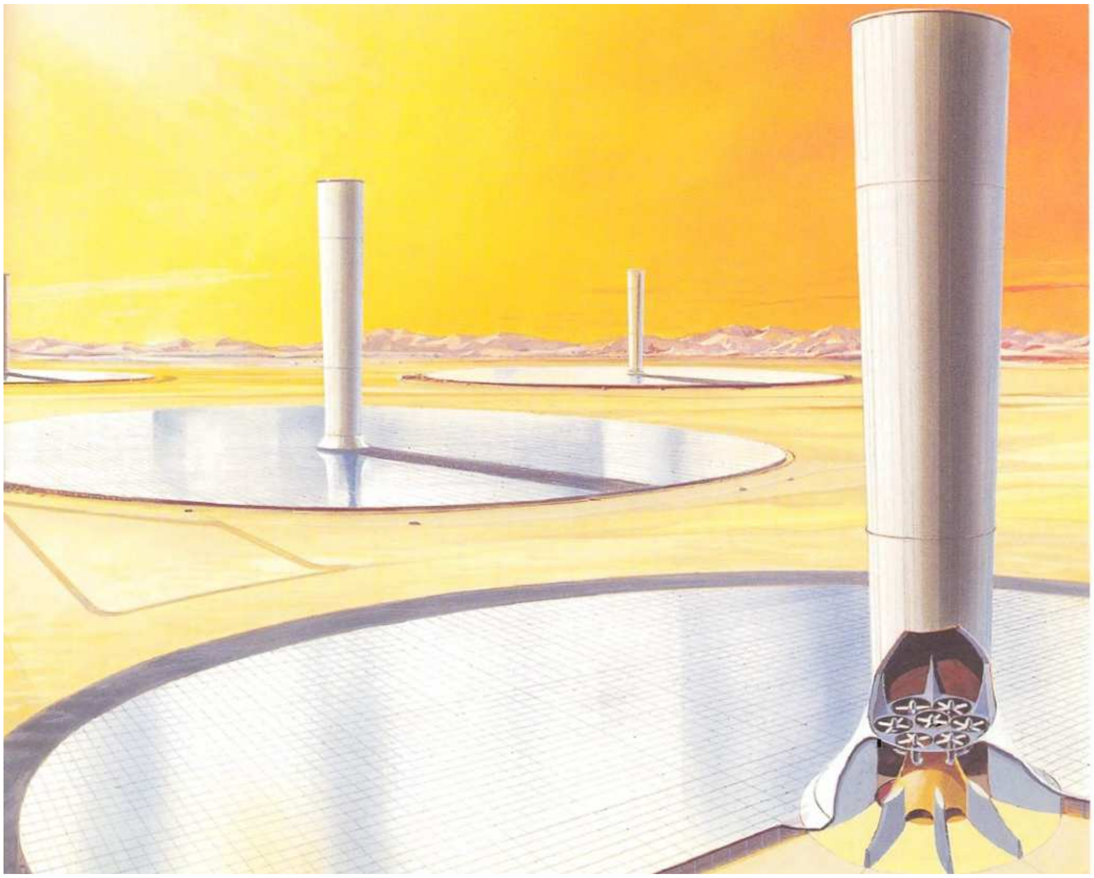

Figure 1-1. An artistic representation of the SCPP [Schlaich 1995].

## 1.5 Thesis development and dissertation layout

The dissertation commences with the formulation of the methodology presented as the argument of the thesis, the Radical Innovation Methodology (RIM), reported in the first part of the document, which is subsequently, in the second part of the document, applied to the problem of the SCPP chimney structure radical innovation.

### 1.5.1 PART I: Formulation of the Radical Innovation Methodology

The first part of the dissertation deals with the development and formulation of the RIM theory. Chapter 2 investigates SE in serving as a comprehensive perspective on a radical innovation: mapping its critical uncertainties in a broader context while breaking it down into its essential functional elements. Chapter 3 investigates MOT as a means of describing and delimiting uncertainty, corresponding to required levels of functionality, through the determination of technological characteristics, maturity and R&D risk. Chapter 4 reports the synthesis of the identified theories into a methodology, thereby formulating the RIM.

### 1.5.2 PART II: Application of Radical Innovation Methodology on the Solar Chimney Power Plant chimney structure

In the second part of the dissertation the validation of the proposed RIM theory is presented: the RIM is applied on the SCPP chimney structure, a technology demanding radical intervention to innovate it up to a state of market feasibility. Chapter 5 introduces the SCPP project as a response to market requirements, sets up a chimney reference case for subsequent use as subject for the RIM application and identifies the required performance of the chimney system to reach market satisfaction. In Chapter 6 the chimney system is broken down into its intrinsic technological elements in order to acquire a functional and technological perspective on the chimney. In Chapter 7 evaluation of the system performance response to augmentation or introduction of individual technologies is performed to identify critical technologies whilst the characteristics, maturity and R&D risk of the critical technologies are assessed in Chapter 8. Chapter 9 concludes part II of the dissertation with a summary of the findings of the previous chapters and subsequent strategy formulation.

The dissertation concludes in Chapter 10 with a summary of the thesis. The contribution of the thesis to the scientific context is verified and recommendations for furtherance of the research are made. The validation of the RIM by means of application on the SCPP chimney is summarised. Finally, the convergence of the improved chimney system performance, as it emerges from the first iteration application of the RIM, to the required performance is recorded in an epilogue.

## 1.6 Thesis scope

### 1.6.1 Applicability of the Radical Innovation Methodology

The RIM provides a basis for radical technological innovation from which organisational competencies required for management of the innovation life-cycle and product diffusion can be interpreted. These aspects are not specifically addressed in this thesis.

Phase-independent RIM application

The principles and logical structure contained in the RIM are applicable throughout the various phases of the radical innovation life cycle, iteratively diminishing uncertainty to a functional, reliable, efficient solution. Although performance criteria may change or become more detailed with project progress [Harrison and Samson 2002], the proof of the thesis is not limited by the phase-dependent characteristics of innovation evolution and technology adoption life cycles. Additional readings describing the phases of innovations include Geoffrey A. Moore's *Crossing the chasm* [Moore 1991] and Everett Rogers' *Diffusion of innovations, 5th edition* [Rogers 2003].

RIM iterations

The RIM can be implemented iteratively up to a state where standard incremental innovation is sufficient for its furtherance, thereby incorporating updated requirement specifications and technical data to refine results and diminish uncertainty onto technological feasibility. In applying the RIM on the SCPP chimney innovation, however, only a single iteration is needed to illustrate the validity of the RIM as a systematising approach delivering information of strategic value.

RIM applicability on technical uncertainty

Radical innovation is often defined and the management thereof grasped through comprehension of the uncertainties it presents. *Technical* uncertainties are related to the integrity and accuracy of the underlying scientific knowledge and technical specifications of the product and its manufacturing, maintainability, etc. *Market* uncertainties focus on customer needs existing in customer-product relations and distribution. *Organisational* uncertainties, stemming from conflicts between the mainstream organisation and the radical innovation team, include issues related to the project team competencies and management support and expectations. *Resource* uncertainties include the availability or acquisition of budget and competencies [Leiffer et al. 2000], as well as the source of the development incentive, varying from market-driven to ecologically, macro-economically, socially or politically driven [Ford and Saren 1996]. Although the creation of radical innovation-friendly organisational competencies and business models are critical for cultivating radical innovation, this thesis is concerned mainly with the resolution of *technical* uncertainties. However, the RIM identifies distinct roles for the technology manager, strategist and expert – these are individually reported. In the application of the RIM on the SCPP chimney innovation all of these roles are enacted. Additional reading discussing organisational topics and competencies include Richard Leiffer et al.'s *Radical innovation – how mature companies can outsmart upstarts* [Leiffer et al. 2000] and Mark and Barbara Stefik's *Breakthrough – stories and strategies of radical innovation* [Stefik and Stefik 2004].

### 1.6.2 Depth engaged in Systems Engineering and Management of Technology

The fields of SE and MOT could contribute a wide range of tools and approaches to expand and extend the RIM. Engineered systems are composed of various interacting resources, e.g. human resources, information, software, materials, equipment, facilities and finances acting over the whole life cycle from conceptualisation through detail design, construction and operation to decommissioning phases. This thesis is only concerned with the synthesis of the basic framework of the RIM and its subsequent application on the set up of a research strategy for the SCPP chimney structure as a validating study. It considers only SE and MOT resources that contribute to the synthesis of a generic formulation of the RIM and, furthermore, those that contribute to the early conceptual phase at which the development of the chimney currently lies. This phase only requires consideration of extreme action configurations as concerns the extreme loading state of structures at fully operational state, as is typical during Structural Engineering designs. Subsequent life cycle analyses could present a comprehensive approach to the broader SE and MOT resources.

### 1.6.3 Structural Engineering scope

Although its principles are applicable to any radical innovation, this thesis implements the RIM only in a Structural Engineering context. It concerns a reinforced concrete concept [Schlaich Bergermann und Partner 2004, Van Dyk 2004] as it is currently defined for a SCPP chimney conceptual solution. Thus, in order to better illustrate the application of the RIM, the scientific context is kept within familiar boundaries (with the exception of less familiar technologies that could be identified during application of the RIM). Thereby this research can utilise the familiar expertise and resources of global and South African (SA) academy and industry in the reinforced concrete field.

The Radical Innovation Methodology might be applicable to resolution of an increasing number of mankind’s radical innovation challenges, managing also those technical problems that go “far beyond the norm”.

# PART I

# DEVELOPMENT OF THE RADICAL INNOVATION METHODOLOGY

# CHAPTER 2

# A VIEW FROM SYSTEMS ENGINEERING

Systems Engineering (SE) concerns the application of engineering toward the solution of a complete problem in its full environment by systematic assembly of subsystems and components in the context of the lifetime use of the system [ICHNET 2007]. This panoptic view on engineering development could provide a perspective on radical innovation from which the radical problem and the source of its uncertainty and required functionality is located, delimited and characterised – the SE concepts required to support this statement are discussed in this chapter. The innovation methodology that serves as blueprint on which the RIM is based is chosen from SE theory and is introduced here.

## 2.1 Definition of Systems Engineering

*Engineering* is concerned with the economical use of limited resources for the benefit of people, satisfying user requirements; to determine how the physical factors can be altered to create the most utility at the least cost. An engineer is forced to create artefacts using incomplete knowledge [Harvey 2007], or *uncertainty*. SE, with "system" defined as an assemblage of functionally related subsystems and components forming a complex, useful whole, involves the interdisciplinary approach governing the total technical effort over the life cycle of the system required to transform user requirements into a system solution [INCOSE 1998]. This definition is chosen from several others because of its inclination to the idea-creation to market-inception definition of innovation. Furthermore, it emphasises the complex, multi-disciplinary and multi-criteria approach needed to understand radical innovation – and the formulation of the RIM.

Blanchard and Fabrycky [2006] defines SE as "good engineering" with emphasis on

- a top-down approach viewing a system as a whole comprising of various components,

- more complete effort to initially define system requirements, in an interdisciplinary (multi-perspective) development approach and
- life-cycle orientation whereby all phases from system functional requirements determination, conceptualisation, design and development, production, distribution, operation, maintenance and disposal are adhered to during decision-making.

Benefits associated with the implementation of SE principles and tools involve the comprehensive and diffused characterisation of market requirements and consequent system development throughout the system life cycle. These result in reduction of system life cycle cost and acquisition time of risk mitigating technologies.

## 2.2 Systems hierarchy

Systems are composed of interrelated components (functional parts), attributes (properties of the components) and relationships (links between components and attributes). A user system is a set of these components interrelated toward a common objective. A system hierarchy breaks the system down from the user system level into smaller subsystems or components through as many levels as are needed to fully describe the system functionality (Figure 2-1 shows a general systems hierarchy down to the lowest level – that of materials). Each level describes the system in more detail. The lower of two systems in a hierarchy is called a subsystem.

USER SYSTEM → PRODUCT SYSTEM → SUBSYSTEM → COMPONENT → MATERIAL

Figure 2-1. General systems hierarchy.

A systems view on development provides a systematic perspective on all facets of the system and those surrounding it in order to identify and delimit critical areas, for subsequent outsourced development. For example, a naval ship (product system[i]) consists of several subsystems like hull, propulsion, weapons and command and control, which in turn consist of various sub-sub-systems (e.g. command and control consists of communication, radar, sonar, action information, etc.).

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[i] A product system is a user system excluding logistical support, personnel, etc.

SE is concerned with the synthesis and integration of *existing* components into higher-level systems and not with their individual development; components are perceived as “black boxes” and should not still be developed during synthesis of the product system (refer to Chapter 1, Section 1.3.1, second subheading).

A *systems breakdown* is the process of dissecting and delimiting the system into its essential sub-systems and components for focused synthesis and R&D purposes.

## 2.3 A systems perspective on the challenge of radical innovation

When a high degree of uncertainty relative to standard design context is encountered at sub-system levels, the augmented uncertainty at user system level make for unmanageable levels of uncertainty (Section 1.3.1) – this states the challenge of radical innovation in SE terms. Figure 2-2 illustrates this in a hypothetical systems hierarchy. Synthesis of a product system incorporates a component that is still under significant development and hence still contains significant uncertainty. Activity concerned only in a single cell (in Figure 2-2) constitutes incremental innovation (a familiar, standardised design environment, portrayed by the small arrows within a single box in Figure 2-2). The uncertainties in lower levels propagate to unmanageable degrees of uncertainty in the higher system levels. Radical innovation occurs across system hierarchy levels thereby *incurring great uncertainties due to venturing outside standardised design environments*.

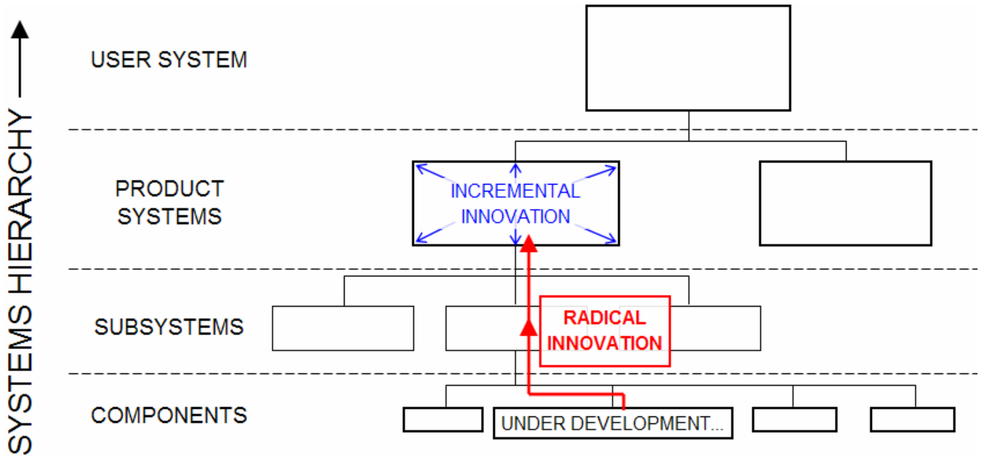

Figure 2-2. The difference between radical and incremental innovation from a SE perspective.

A systems perspective on radical innovation could provide a framework from which the extent and delimiting of uncertainty are determined. The developer could isolate the source of uncertainty in terms of the systems level, life-cycle phase and scientific field it originates. He could then decide, based on the perceived risks of the specific development up to sufficient certainty, whether to focus on in-house development, technology acquisition (transfer from external sources) or the termination of research.

## 2.4 Systems hierarchy breakdown, functional allocation and failure mode identification

The systems hierarchy breakdown, failure mode identification and functional allocation are performed to logically determine which technologies are present in a system. These perspectives are implemented and integrated to ensure that all critical user-required and failure mitigating functionalities are incorporated in the user system.

### 2.4.1 Systems hierarchy breakdown

The hierarchical breakdown of a system into its essential functional components provides top-down insight into each functional part. All functional modeling commences by formulating the overall system function. By breaking the overall system function into small, readily diffusable sub-functions, the form of the system follows from the assembly of all sub-function solutions [Tumer and Stone 2001]. It is hard for a manager to decide at what level of detail such analyses must be carried out and could lead to a listing and evaluation of every functionality in the system. Rather, the aim is to obtain an understanding of the overall system and of the critical developmental issues, functionalities and uncertainties presented [Ford and Saren 1996].

### 2.4.2 Failure modes and their relation to functionality

A failure mode is any manner in which a system element fails to accomplish its objective [INCOSE 1998]. Blanchard, when defining failure from a systems perspective, states that a *failure* has occurred any time the system, on any level of the system, is not *functioning* properly – failure occurs, therefore, due to the *absence* of function [Blanchard and Fabrycky 2006]. These absent functionalities can be identified in a comprehensive method and framework within the defined systems hierarchy. The identification of failure modes and their root causes, provide important direction to the functionality that needs to be addressed in the system synthesis. It is therefore essential to identify as many as possible critical failure modes in a system.

While regarding prior knowledge and experience as essential input, several tools toward failure mode identification exist, including Failure Mode Effect and Criticality Analysis (FMECA) and Failure Tree Analysis (FTA) [Blanchard and Fabrycky 2006].

### 2.4.3 Functional allocation

A *function* is a specific action necessary to achieve an objective. Functional allocation forms part of the determination of system requirements which adheres to user requirements through technical responses and design attributes stating *"how"* the user specified *"what"* is satisfied [Blanchard and Fabrycky 2006]. The functional description of a system serves as a basis for identification of the technological functionalities required in the system for it to accomplish its objectives; design synthesis can be aimed at specifically addressing these requirements. The uncertainties in lower levels perpetuating to higher levels could be engaged through the determination and allocation of functionality at positions of uncertainty in the system, and not through the limiting procedures of standardised design practice.

During functional allocation, the requirements are diffused from user system level as far down the hierarchical structure as is deemed necessary to assign critical input design criteria for the essential elements of the system. Functional allocation presents a description of the functionalities of the system to establish a functional performance baseline in terms of user requirements for subsequent design and support activities [Blanchard and Fabrycky 2006].

### 2.4.4 Linking failure modes and functionality to technology

The fundamental definition of technology as *created competence* [Van Wyk 2000] predicates a positive link between the functionalities of a system and the technologies bringing into being (creating) the qualities in a system that enables it to fulfil its objectives (competence). Functionality states *what* is required; technology determines *how* the requirement can be addressed.

Samsung Advanced Institute of Technology (SAIT) determines R&D themes (see Figure 2-3) in response to identified failure modes in a technology performance specification phase.

These themes are addressed through a *technology tree* that stipulates technology flow from the R&D theme to systematically deploy the key functions, thereby implementing corresponding core technological solutions [Cheong 2006].

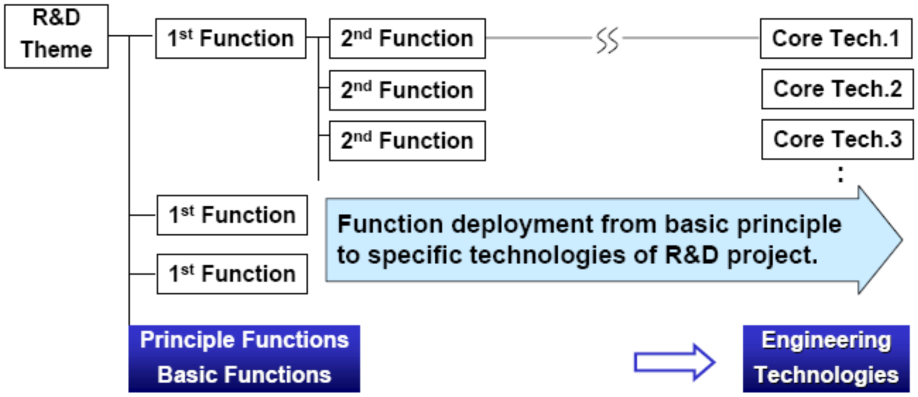

Figure 2-3. The link between R&D theme, functionality breakdown and core technology identification [Cheong 2006].

## 2.5 Further Systems Engineering concepts

This section introduces SE concepts that may prove helpful in understanding of further aspects and approaches surrounding the development of the RIM.

### 2.5.1 System baseline and the Ideal Final Result

A *baseline* (section 2.4.3) against which a given alternative or design can be evaluated, is established early in the development process, typically specifying the functional requirements that the system must perform in order to satisfy user requirements. Baselines are expressed in terms of technical performance measures that are defined as goals for each appropriate system level [Blanchard and Fabrycky 2006]. In radical innovations the user-required baselines might be far from currently achievable technology performance, the technological limit representing a metric that has to be surpassed to obtain breakthrough.

At this stage, the introduction of the Ideal Final Result (IFR), a lateral, non-incremental approach to problem solving, is apt. IFR directs the technology developer to the *raison d'être* of technological endeavour – the solution of an identified need – as opposed to mere incremental improvement for gaining market share, thus encouraging non-standardised, problem oriented thinking [Shirwaiker and Okudan 2006]. The IFR is defined as the "absolutely best solution of a problem under the given conditions" [Savransky 2000].

Technological *contradictions* are that which inhibit technological innovation. *Ideality,* on the other hand, presents the notion that a contradiction (e.g. transport from point A to point B uses too much fuel due to work performed to move weight) can be opposed by an ideal solution (that of using less fuel, through, for instance, significant decrease of the transporter weight). While envisaging the IFR as a *reverse engineering* approach, investigating solutions *starting from* the IFR and reversing to currently feasible capabilities, may direct radical innovation strategy from its current inadequate status, toward an acceptable solution. This could possibly gaining technological performance 'distance' further than incremental thought and methods would allow.

In this thesis IFR is interpreted as the license to conduct what is termed *virtual probing*. It may be beneficial to, for the purpose of understanding the impact of a future technology improvement, perform a *virtual probe* [Van Dyk 2006] where technologies are allowed to be augmented outside the extent of their physical limits (as currently perceived) by assuming a 'what if' stance to their performance improvement. *Probe* is defined as the "enquiry into unfamiliar or questionable activities" [Webster 2008]; *virtual* probe then essentially constitutes the artificial augmenting of technological capability. Through the *virtual* augmenting of technological parameters or concepts vital insight into system performance response can be gained. This lateral approach, thinking 'outside the box', creates opportunity for radical innovations to materialise; incremental innovation practice would outlaw this radically innovative approach on the basis of its higher risks, greater expense and non-compliance to standardised design limits. It may be argued that moving outside physical technological limits is unprofitable (because it is perceived as being unrealistic) but the IFR concept supports the notion of looking toward the *preferred* solution, rather than the *realistic* solution in order to proceed with development in a way better directed to the optimal solution.

### 2.5.2 Performance criteria

Choosing performance criteria for radical innovations

User defined requirements form the base from which criteria for system evaluation is identified. System performance evaluation must address all the governing facets that pertain to the performance of the system. System performance evaluators often measure radical innovations with the same criteria used to assess incremental innovations, leading to autocratic decisions based on mainstream business principles or idealistic numbers based on questionable assumptions [Leiffer et al. 2000]. Initial decisions about growth opportunity promised through the realisation of a radical innovation must be based on the deliverable benefits of the innovation and on market size if the envisioned benefits are delivered.

Identification and breakdown of criteria

The first formal evaluation of a radical innovation generally takes place when the project applies for funding. Initial evaluation must determine whether there is enough promise to warrant the next step by the investor [Leiffer et al. 2000]; the criteria chosen for the evaluation of *radical* innovations must capture the contribution of envisioned technological benefits and market impact sufficiently to convince potential investors to invest in the next development phase.

As innovation evolves along its life cycle, more detailed investigation and certainty is required; similarly the criteria on which a system is evaluated incorporate more detail with increasing system depth. Table 2-1 illustrates this point by depicting typical criteria at pre-construction phases of a project. In *radical* innovations the earliest developmental phases may include a broader-than-standard range of criteria due to the fact that the conceptual 'feasibility' must be proven to potential investors in light of the sought *functionality* amongst uncertain multi-disciplinary surroundings. This entails comprehensive investigation into new functional (technological) or scientific fields with their own sets of governing criteria.

A perspective on the breakdown of functional performance evaluation criteria which aid the choice of criteria, is based on work by Fusfeld [1978]. *Primary criteria* pertain to the fulfilment of a system's primary purpose. The *secondary criteria* pertain to the establishment of structure and containment to enable the system to perform its primary function. Resources needed to develop or produce primary and secondary functionality, e.g. production time, direct further choice of criteria.

Table 2-1. Typical criteria at various life-cycle phases.

| System life-cycle phase | Example of governing criteria |
|---|---|
| Radical innovation phase | Benefits of technology in terms of potential market share |
| Conceptualisation | Primary user-required function<br>Conceptual reliability, structural performance<br>Estimated cost, also of required R&D |
| Pre-feasibility | Structural reliability<br>Overall construction cost<br>R&D cost<br>Maintenance cost<br>Maintainability<br>Constructability<br>Environmental impact |
| Feasibility | Structural reliability (in depth validation)<br>Maintainability<br>Maintenance cost<br>Detailed construction cost (materials, transport, labour, contracts, etc.)<br>Constructability<br>Environmental impact<br>Political, social and technological feasibility<br>Supportability<br>Disposability |

### 2.5.3 The complexity of radical innovations

Radical solutions, and especially those geared to sustainable, holistic solutions, are generally complex systems that have to adhere to a broad range of non-standard requirements to achieve success. Similarly to the several two-dimensional images required to convey all the geometrical information of a three-dimensional object, the complexity of these systems cannot be known in one glance and has to be viewed from several less encompassing perspectives, each revealing distinct information in order to understand the whole.

Furthermore, because non-standard perspectives may be unfamiliar, the impact of developments in the system could be non-intuitive requiring significant familiarisation and modeling efforts. Solutions may also emerge from unpredicted, unfamiliar sources.

An active approach must be adopted to incorporate, within managed resource expenditure, all perspectives that could contribute critical impacts on the system state; standard criteria cannot merely be assumed because they do not necessarily provide prominence to critical areas of the system.

In order to accommodate decision-making where multiple criteria are concerned, Multi-criteria decision-making methods can be utilised to view the impact of technological change on the attractiveness of a system; an overview of these methods is provided by Triantaphyllou in *Multi-criteria decision making: an operations research approach* [Triantaphyllou et al. 1998].

## 2.6 Systems analysis process – a model for innovation

Successful technological innovation requires the innovation process to be well managed. Attempts to model innovation reveal it to be very complex. No model appears to be representative for utilisation as a general model of innovation, failing to recognise the cumulative, complex and often disorderly nature of innovation. One report, focusing on technical and market competencies of a firm, states that half the respondents used for its study did not have a formal process for assessing the strategic value of an innovation to their businesses [Harrison and Samson 2002].

### 2.6.1 Innovation models

Several models attempt to identify characteristics that define innovation – organisational and technical attributes that require cultivation to differentiate core technical capabilities and market insight toward effective innovation. Innovation models attempt to capture the following two traits, depending on their application [Harrison and Samson 2002]:

- sequential linear activity with functional responsibility stages defining distinct points for decision-making during the innovation process, and
- a conversion process from technological opportunity to marketplace needs.

### 2.6.2 The systems analysis process

The innovation model chosen as representative of the basic steps of technical innovation on which the RIM is based is provided by standard SE theory in the *systems analysis process*, shown in Figure 2-4. The principles and procedure for analysis of system solution alternatives, presented by the systems analysis process, provides systematic steps to determine system performance in terms of specified user requirements. These steps may prove to be useful in radical innovation for the evaluation of system performance.

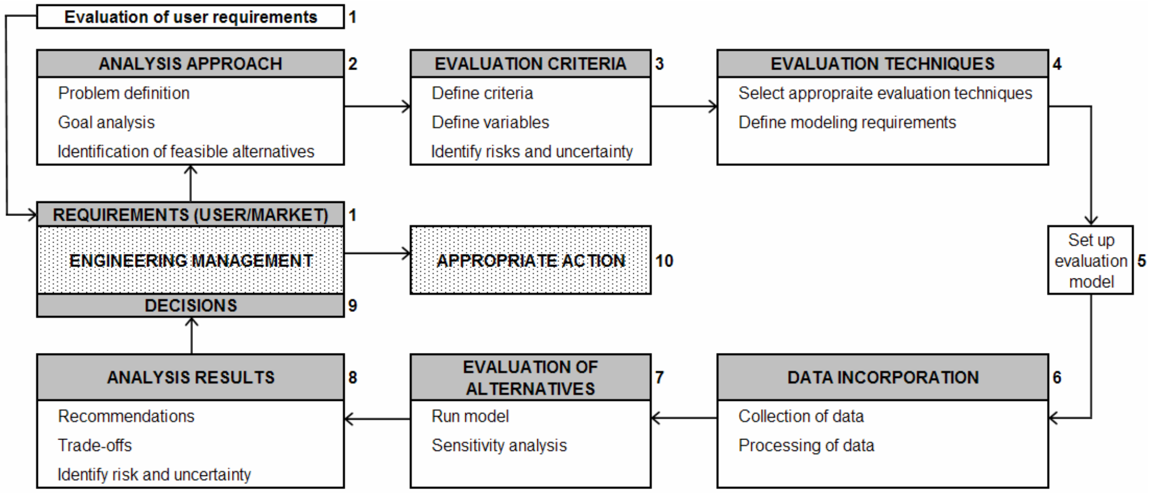

Figure 2-4. The systems analysis process [based on Blanchard and Fabrycky 2006].

The model starts with the evaluation of user requirements (1)[ii]. Market requirements and uncertainties must be understood and diffused to direct technical development. The analysis approach (2) continues the process with comprehensive problem definition, specific goal analysis and the proposal of feasible alternatives. Evaluation criteria (3) are set up and variable risks and uncertainties identified. Evaluation techniques (4) involve the choice of the appropriate evaluation and simulation techniques. The evaluation model is set up (5) followed by the collection and processing of data (6). Alternatives are evaluated (7) by way of an evaluation model and these results are analysed and interpreted (8) with reference to recommendations, possible trade-offs and strategic risk and uncertainty. Decisions are made and strategy formulated (9) governing appropriate consequent action (10). Note that

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[ii] Number of block in Figure 2-4.

Engineering Management (dotted blocks) manages the processing and diffusion of requirements and decision-making between the strategic and R&D divisions.

Although fairly linear, this model incorporates the traits mentioned in section 2.6.1 of converting user requirements to active strategic decision through distinct phases evaluating the state of the system. Proposed solutions (alternatives) are evaluated in terms of their fulfilment of the user specified criteria (representing system complexity) and technical performance measures. The iterative implementation of the systems analysis process model gathers increasing insight toward sound decision-making [Blanchard and Fabrycky 2006].

## 2.7 Conclusion

This section introduces SE principles as a framework from which radical innovation can be understood and managed more systematically and efficiently. The top-down view of SE, breaking user-required functionality down into hierarchical levels, allows the technology manager a comprehensive perspective on the system for subsequent delimiting and characterisation of its areas of opportunity and uncertainty which could be addressed through the application of MOT.

SE contributes useful theory to innovation management. Its approaches and tools could be of substantial benefit to radical innovation. The systems analysis process, a systematic innovation model, is introduced whereby a system is proposed as a solution in response to user requirements, evaluation criteria are distinctly specified, a model toward evaluation is set up and data is collected and entered into the model toward the evaluation of alternatives. Evaluation results are formulated into strategy.

During the implementation of the systems based approach on radical innovations it is imperative to characterise the current standing of the functionalities – and their ensuing technologies – in the system in order to deal with the actual units of improvement and quantify uncertainties from a technological perspective; also for identification of similar technologies and technological trends from technology scanning and foresight procedures. In the next chapter such a technological perspective is proposed that could aid radical innovation through ‘filling in the gaps’ exposed by the systems perspective.

# CHAPTER 3

# MANAGEMENT OF TECHNOLOGY: APPROACH AND TOOLS

SE provides a logical framework and procedure to delimit and identify functionality and associated uncertainty in the radical innovation. In this chapter Management of Technology (MOT) theory is investigated for its potential contribution in describing these technical uncertainties through the determination of technology characteristics and maturity.

The chapter commences with a definition of technology and background on MOT. Subsequently MOT approaches and tools for technological assessment, scan, foresight, trend identification and strategising are investigated.

## 3.1 Definition of technology

The word “technology” is a widely abused term usually summoning images of high-tech gadgets when in reality it is the building blocks of engineering endeavour – the “major stimulus for change in society” [Twiss 1992] – and the mechanism by which mankind leverage its efforts to improve his quality of life [Harrison and Samson 2002]. It is not the “grey mist floating” behind the products of a company [Ford and Saren 1996]. Insight into technologies could add vital insight into the elementary subsystems comprising the user system. Rather than characterising the whole through a semi-empirical approach, a technological perspective is the “most potent ingredient” for understanding and advancing the capabilities of systems [Blanchard and Fabrycky 2006]. A fundamental definition of technology describes it as “created competence” [Van Wyk 2000] (mentioned in section 2.4.4), i.e. bringing into existence a competence toward a set of inherent qualities that interacts in a wider socio-economical environment [Harrison and Samson 2002].

Technology can be characterised as a unit of analysis in measuring progress of a company, serving as a basis for strategy development by evaluating overall technological position and performance. This comprehension of technology could prove critical in conditions of unpredictable technological change and uncertainty [Ford and Saren 1996] as typically encountered in radical innovations.

## 3.2 Management of Technology background

Management of Technology (MOT) concerns the core theory of technology and its engineering dynamics, innovation, project management and policy in an ethical, environmental, economical and political context [Van Wyk 2004a, Steele 1989]. Its approach and tools aim to provide companies and researchers with a handle on their technology portfolio in order to grasp their standing relative to competitors and manage technology as their primary assets [Harrison and Samson 2002]. Its perspective on technology could provide the radical innovation process with a means of characterising and delimiting technological status, potential and uncertainty.

### 3.2.1 Technology theory

Apart from the organisational competencies sought through MOT, proponents of its theory believe that formulation of a fundamental structure for technology theory could greatly improve understanding, management and implementation of this all-important commodity, forming a framework against which all the details of an individual technology can be mapped. Classification and characterisation would prevent corporate managers from being blindsided by new technology and enable them to systematically map their technological environment and predict definitive developments [Van Wyk 2004a].

Although technology has not undergone that profound comprehensive classifying simplification that marks the development of most fields of knowledge as they grow toward maturity (e.g. Chemistry’s periodic table of chemical elements), recent decades saw renewed focus toward this goal with the definition of key concepts and frameworks clarifying technological thought [Van Wyk 2004a].

### 3.2.2 The value of technology theory for radical innovation

The application of SE on the radical innovation problem yields a comprehensive perspective on the system for delimiting, and subsequent characterisation, of areas of opportunity and uncertainty. The assessment of technologies in a system engages the actual units of improvement – functionalities, the system's building blocks – and quantifies uncertainties and opportunity for improvement as seen from a technological perspective. Figure 3-1 illustrates this point through an example of a system hierarchy depicting hypothetical technological information (the graph in each box display typical technology growth curves; these are elaborated later in this chapter) on the functional (i.e. technological – refer to Section 2.4.4) breakdown of each level with the large arrows indicating more potential for growth. Regions promising large potential for growth based on their technological maturity, for instance the graph on the right at subsystem level, can be isolated for specific R&D focus.

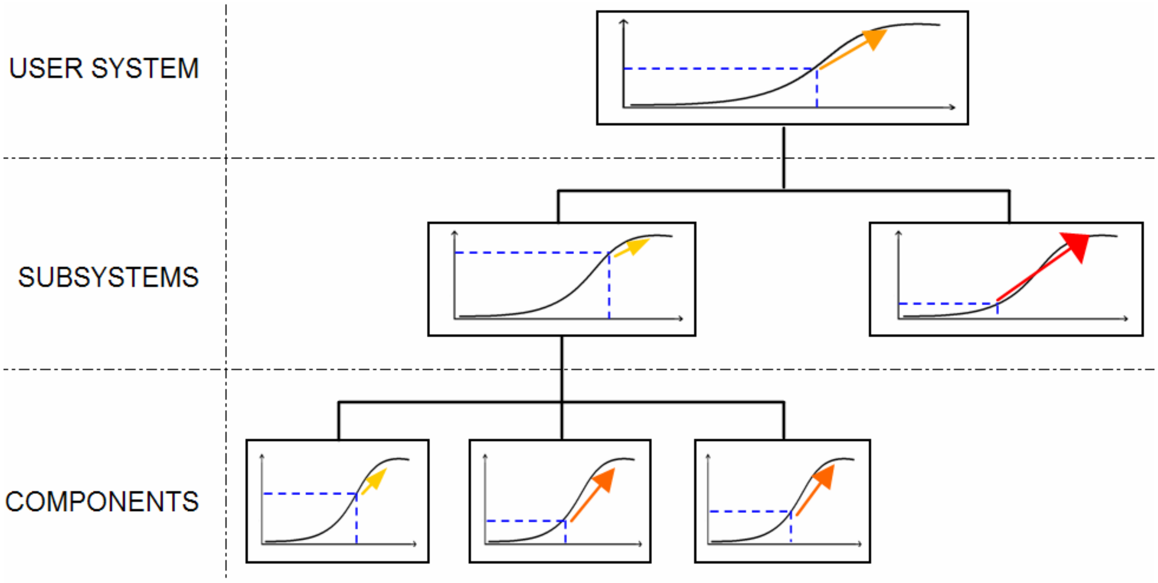


Figure 3-1. Technology growth curves of system functionality at various levels provide information on its growth potential.

Technology characterisation and classification qualifies the current technological standing contributing technological insight from which technology development can be managed efficiently. Similar technologies can be identified from technology scanning procedures for potential acquisition. Technology trend identification and foresight provide systematic attempts to predict the growth of technology.

This chapter continues by providing approaches and tools focused on the gain of technological insight. Although the field of MOT covers a wide range of organisational and managerial approaches, only theory that is deemed directly applicable to the development of the RIM is included in this thesis.

## 3.3 Technology assessment

Technology assessment deals with the characterisation and classification of technology, i.e. the description of distinctive, differentiating features. Technology assessment as defined by Ford and Saren [1996] provides a qualitative base from which to concentrate on strategising technological R&D. It concerns the circumscription, characterisation, completion and classification of a technology portfolio, the determination of technology origin, maturity and company competence, and the performance of the company to manage, exploit and acquire technologies.

*Strategic Technology Analysis* (STA) is a recent initiative proposing distinct tools based on technology theory, aimed at assessing technologies and technology fields. Technologies are interpreted through several frameworks on the grounds of their intrinsic characteristics. A technology is proposed as an *entity*, i.e. dissectible and distinguishable, having *internal* features [Van Wyk 2004a]. This implies a possibility for its analysis. The technology features and frameworks presented by STA are introduced here to classify and characterise technologies.

### 3.3.1 Technology characteristics

Technologies can be grouped in terms of inherent characteristics or *internal potency*. Dissection of a technological entity and identification of its unique features give rise to the formulation of the *Framework of Basic Features* (Table 3-1) with seven distinctive technology character traits identified and accompanied by a practical question [Van Wyk 2004a]. The Framework provides and enforces a comprehensive perspective on the technologies in a system to also identify the non-intuitive features. The Framework is typically used to structure technological presentation and propose a common frame of reference and terminology, as well as communication, for specialists presenting to non-specialists. The Framework also provides the starting point from which other frameworks in the STA are approached.

Table 3-1. Framework of Basic Features [Van Wyk 2004a].

| Characteristic | Question |
|---|---|
| Function | What does the entity do? |
| Principle of operation | How does it do it? |
| Performance | How well does it do it? |
| Structure | How is the entity composed? |
| Fit | What is the hierarchical position? |
| Material | What is the entity made of? |
| Size | How large is the entity? |

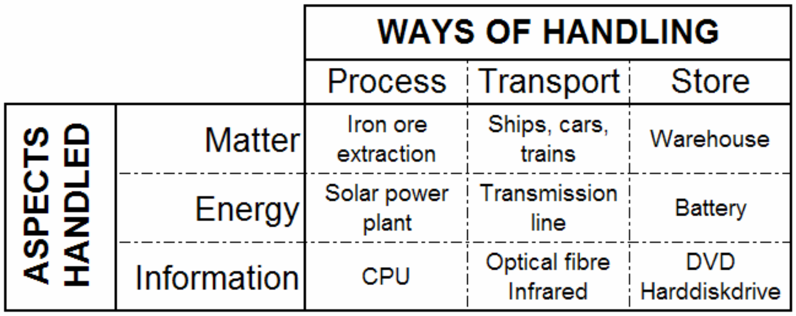
The *theory of inventive problem solving* [Altshuller et al. 2001] is a methodology for generating innovations. It also defines typical characteristics that describe the physical state of a technical system. When solving technical problems these characteristics help identify the technical contradictions residing in the problem. Being intrinsically focused on problem solving, its list of typical technology characteristics is of a more practical nature than the mere identification of basic features by the Framework of Basic Features, investigating also the technological environment to identify solutions.

### 3.3.2 Classification of technology

Technology taxonomies provide a logical information framework whereby all kinds of information from definition, capabilities and material properties to typical modeling are organised and made accessible [IMTI 2003]. The relative potency of technologies in the system are grasped and placed within the greater context of technologies in the technological landscape in order to identify similar technologies to be assessed for potential acquisition.

Medical [Evans 2005] and manufacturing technology [IMTI 2003] are fields where progress was made toward setting up comprehensive technology taxonomies focusing on creating a technological information base capturing and exploiting knowledge, experience and data to provide “access to *the right information at the right time at the right place*” [IMTI 2003].

In investigating taxonomical characteristics of general technology the following is identified: the three fundamental aspects of physical reality can be classified as matter, energy or information which is handled in one of three modes, namely process, transport and storage. All technologies can thus be connected in terms of their basic function and presented in a coherent matrix called the *Nine Cell Technology Functional Classification Matrix* (Figure 3-2) [Van Wyk 2004a]. The figure contains examples of technologies fitting the nine categories, for example, DVD technology storing information (bottom right cell in Figure 3-2).



| | | WAYS OF HANDLING | | |
|---|---|---|---|---|
| | | Process | Transport | Store |
| ASPECTS HANDLED | Matter | Iron ore extraction | Ships, cars, trains | Warehouse |
| | Energy | Solar power plant | Transmission line | Battery |
| | Information | CPU | Optical fibre<br>Infrared | DVD<br>Harddiskdrive |

Figure 3-2. Nine Cell Technology Functional Classification Matrix [Van Wyk 2004a].

## 3.4 Technology scan

Technology acquisition is the process of identifying beneficial technologies outside the company's portfolio and its transferral, insertion and integration in the company [Ford and Saren 1996]. *Technology scan* involves the familiarisation of the technical system with its broader technological environment, or *technology landscape*, through an understanding of the characterisation and classification of internal (to the system) and external technologies. The market relevance of internal technologies is assessed and similar technologies identified from the landscape for acquisition of their relevant elements. The applicable technology landscape, containing knowledge relevant or peripheral and lateral to the subject (constituted by the sum of expert knowledge, journals, conference proceedings, etc.), is scanned for identification of technologies that could fulfil the functionalities specified by the system functional architecture. Furthermore, the identification and acquisition of an emerging technology that fulfills the same functionality of a mature enabling technology can provide significant competitive advantage.

Technology scan involves the meeting of cross-disciplinary experts each contributing from his field of knowledge, "challenging and stretching conventional thinking" on the best solution and practice [Floyd 1997]. The scan must not be limited to familiar or developing technologies and must include competitor and untried technology alternatives. A scan could also look to nature for acquisition of its tried-and-proven ‘technological’ solutions [Stefik and Stefik 2004].

The complex, multi-disciplinary nature of radical innovations could make technology scan an integral stage toward the solution of the radical problem – looking outside the constraints of conventional design. Radical innovation would typically require a more extensive technology scan in an attempt to investigate all potential contributing technological avenues.

## 3.5 Technology roadmapping

Technology roadmapping provides structured, flexible techniques for planning technology development support and long-range technology strategy. Its efficacy in recent years has led to a wide range of definitions and purposes of and for roadmaps, exploring and communicating the relationships between evolving and developing markets, products and technologies over time [Walsh 2004, Phaal et al. 2004]. The impact of technological and market changes can be anticipated in terms of potential threats and opportunities [Phaal et al. 2004] and strategy can be formulated proactively.

Technology roadmapping entails approaches and a broad spectrum of tools to aid in the identification, selection and development of technological alternatives to satisfy a set of product needs [Walsh 2004]. A team of experts are co-opted for organising and presenting the critical technology-planning information to make and leverage informed investment decisions. Needs are identified and addressed through technologies that, upon investigation, are found to be critical to the realisation of required performance targets. Development of these technologies up to the sought performance targets can be specifically managed and its time frames calculated. The extent of the knowledge base serving technology roadmaps is vast; texts providing introductory reading on the evolution and current status of technology roadmaps include [Phaal et al. 2004, Phaal and Muller 2008, Walsh 2004].

Roadmaps are concerned with mapping the uncertainties of the “future” – vision, goals and potential change. Threats and opportunities may be radical or disruptive, in nature; a legitimate concern about many roadmap formats is that they are biased in favour of the preconceived, preferred development route. Healthy roadmapping should accommodate potentially disruptive uncertainties [Phaal and Muller 2008]. Some efforts have been made to expand the applicability of roadmaps to cover longer periods of development, reaching into higher levels of uncertainty and absence of knowledge base. Gerdsri and Kocaoglu [2003], Vojak and Chambers [2004], Walsh [2004] and Kostoff et al. [2004] characterise the developmental phenomena typical of roadmaps for disruptive technologies. These draw mainly on business, managerial and MOT insights to formulate perspectives and methodologies to identify and develop or manage against potentially disruptive technologies. Their results serve as useful parallel reference for the independent study performed for the proof of the thesis subject in this dissertation, aimed at drawing on existing, fundamental bodies of knowledge.

The successful implementation of technology roadmapping as a managerial tool has brought about the creation and acceptance of similar techniques such as technology foresight and forecasting as well as data scanning [Walsh 2004].

## 3.6 Technology foresight

Where the technology scan and roadmapping approaches provide insight in the current and preferred technology states, *technology foresight*, defined as a systematic attempt to look into the future of technology, society and the economy, could extend it by identifying trends and predicting social, economic and environmental niches for pro-active technology strategy. The long-term nature of some systems, e.g. most civil engineering projects and large facilities such as ships or aeroplanes, leave them particularly vulnerable to uncertainties arising from unforeseen changes [Ford and Saren 1996]. Technology foresight is an expert-based approach to developing medium to long-term strategy by extrapolation of existing patterns to minimise risk during long-term project planning.

Technology foresight suits the characteristics of radical innovation well, explicitly recognising that the future is uncertain and that seriously disruptive events can and will happen. Practical benefits of deploying foresight approaches are the receptiveness and response to signals of change and better judgement for resource allocation [Johnston 2003].

## 3.7 Technology trend identification

The value of a technology can be related to a combination of its performance improvement and an assessment of its maturity and the risk associated with R&D up to the required performance level. A new, emerging technology holds great potential simultaneously with significant uncertainty with regard to its actual development up to profitable status while, on the other hand, a mature technology presents low risk solutions with lower return on investment. *Technology trend curves* and the *Cascade of Technological Trends* are tools included in STA in order to evaluate technology maturity toward strategy formulation [Van Wyk 2004a].

### 3.7.1 Technology trend curves

The technology S-curve and other technology trend curves

Various types of visualisations are used to describe technological trends. Curves depicting change of technological parameters relative to resource expenditure are used to portray change in characteristics of relevant metrics of performance [Van Wyk 2004a].

The *technology S-curve* [Abernathy and Utterback 1978] depicted in Figure 3-3 displays a typical growth phenomenon in technology.

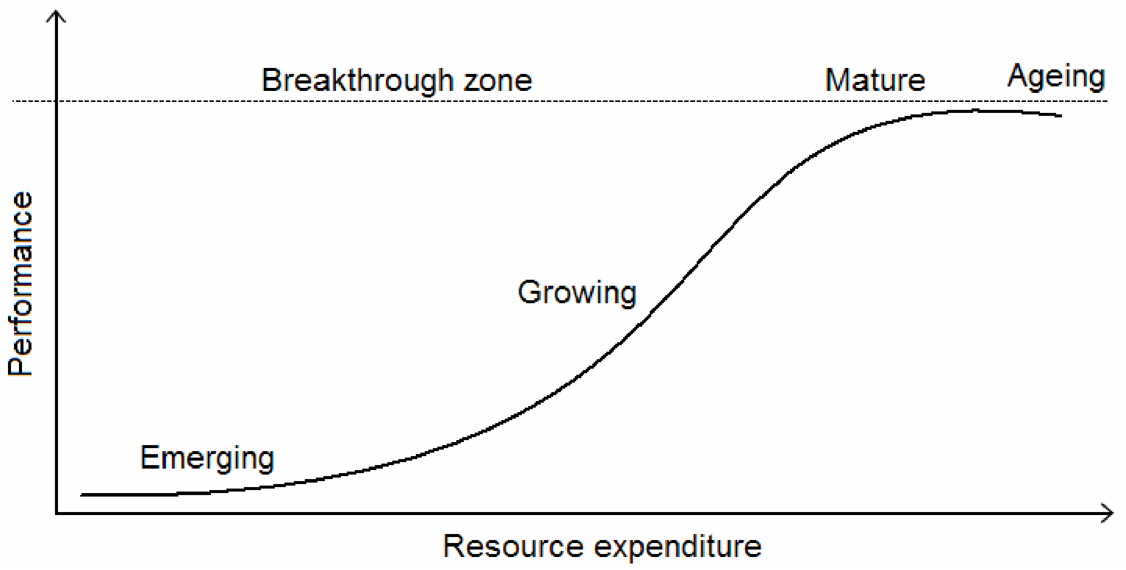


Figure 3-3. Typical shape and phases of the technology S-curve [Abernathy and Utterback 1978].

The *emergence* phase of a technology is characterised by a low gradient performance increase relative to resource expenditure implying high risk, high return R&D investment. Higher gradient performance increase presents a *growth* phase, with subsequent decreasing performance increments signifying the *maturing* phase where R&D investment is of fairly low risk with low return on investment. During the *aging* phase, technology becomes obsolete, nearing the *breakthrough zone* (also known as a technology threshold [Ford and Saren 1996]) which is a physical or socio-economical barrier to technology performance growth. At this phase there is a strong incentive for advancing R&D into unchartered territory [Van Wyk 2004a] to develop radical, disruptive technologies for better performance solutions [Ford and Saren 1996, Christensen 1992]. SE defines factors that stand in the way of attaining objectives as *limiting factors*. Location of limiting factors enable the identification of factors that *can* be altered to make progress possible, referred to as *strategic factors* [Blanchard and Fabrycky 2006], these becoming critical focus areas in the development process.

The actual shape of S-curves is seldom as elegant as portrayed in Figure 3-3. Periods of continuous incremental change are often interspersed by shorter periods of radical discontinuities [Ford and Saren 1996]. Radical innovation technology growth curves are particularly spread with starts and stops, detours and waxing and waning of funding [Leiffer et al. 2000], requiring vision, endurance and patience during strategic decision-making.

Other technological trend curves include size and cost curves depicting improvements in specified parameters (e.g. the increase of the capacity of a computer CPU over time). Substitution or diffusion curves [Christensen 1992] (see Figure 3-4, depicting substitution of material platform technologies used in integrated circuits over time [Bowden 2004]) describe the pattern in which an existing technology is disrupted and replaced by a new technology. Early scanning for and acquisition of substitute technology is needed when technologies near maturity and obsolescence to assure timely succession of next generation technology.

Parameters to be used as performance criteria include technological performance capabilities (storage density, reliability, capacity, etc.) of the trend-assessed technology or the number of publications or patents filed within a particular technological field. Although the latter methods have drawbacks due to varying publication quality, research focus, differing national patent laws and secrecy, the method does have the advantage of simplicity [Savransky 2000].

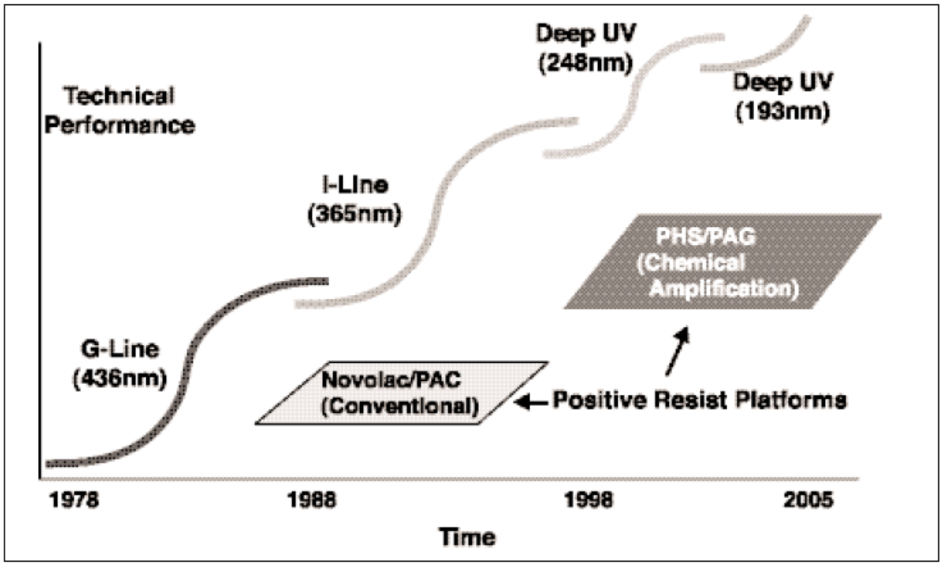


Figure 3-4. Substitution of material platform technologies in integrated circuits [Bowden 2004].

Subjectivity of trends

Technological growth is easily manipulated by factors that are not technical in nature but responds to non-technical, firm specific, political, social or economical pressure [Christensen 1992]. The immense impetus that political purpose and military endeavour provided to the radical scaling of technologies during the Apollo space project [Murray and Bly Cox 1989] and the two world wars is evident through the incredible range and depth of innovation following these events [Comstock and Lockney 2007].

### 3.7.2 Cascade of Technological Trends

Technological change occurs in distinct cascades and could therefore identify the current level of technological development and predict the typical future focus for technology R&D. Five cascade levels are observed in the *Cascade of Technological Trends* (Figure 3-5) [Van Wyk 2004a] providing insight into the level of development of a technology. At Level 1 material function and structure are the main parameters of change. Level 2 improves structure, principle of operation and size. Level 3 accounts for improved performance and Level 4 for decrease in cost and improvement in safety and health issues and environmental impact. Level 5 investigates technology substitution and diffusion into its relevant markets.

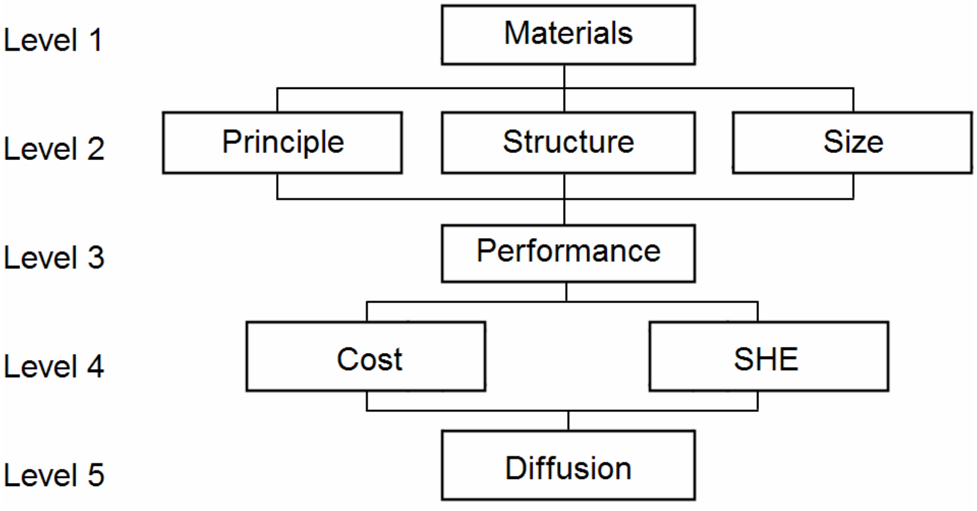


Figure 3-5. Cascade of Technological Trends [Van Wyk 2004a].

## 3.8 Strategising technology development

Technology strategy connects business goals to market requirements through consideration of technological prowess [Harrison and Samson 2002]. Throughout the technology identification, assessment, scan, foresight and trend identification phases, a foundation of insight into the current and potential technology position is gained, differentiating it from a wider technology landscape. This equips the technology manager for pro-active response to changes in the technology landscape enabling pro-active shifts with regard to technology strategy.

The field of MOT contains approaches and techniques to assist in the formulation of technology strategy. These include the setting up of R&D roadmaps [Harrison and Samson 2002] and technology R&D risk assessment.

### 3.8.1 Strategy maps

Strategy maps are used to visualise technological data for the formulation of strategy, examining the interactions and balances between perspectives for each alternative in a given scenario [Yu 2005]. Consider as an example *Technological Position Analysis* which is a tool to determine which technologies are in a position to make critical contributions to improving system performance and market satisfaction [Clausing 2001]. Figure 3-6 portrays an example of a Technological Position Analysis map displaying customer satisfaction against technological strength with subsequent technological priorities. The high satisfaction–high strength areas describe a company's core competency (Technologies T2 and T3 are developing toward that area, their small size indicating emerging and growing technologies while T1 is mature, moving away from core influence because of displacement by succession technologies).

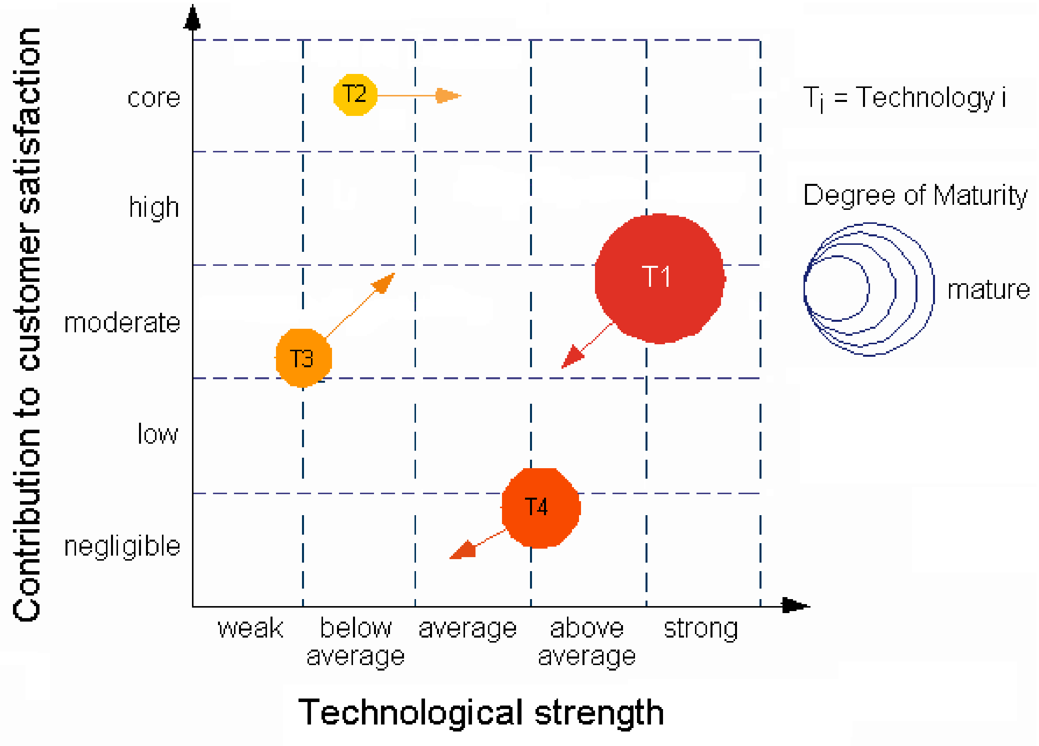


Figure 3-6. A strategy map depicting technological position [adapted from Clausing 2001].

Many other strategy techniques and tools exist in managerial theory. A useful initial reading elaborating on strategising techniques and tools is provided by the text *Strategic management of technology and innovation, 4th edition* [Burgelman et al. 2004]. Technology roadmapping (discussed in Section 3.5) contributes a further knowledge base on the spectrum of technology strategy visualisation methods [Walsh 2004, Phaal et al. 2006].

### 3.8.2 Research and development risk

Technology trend curves suggest the depth of R&D resource allocation needed to realise the augmented level of performance, or the technology identified for introduction to the system. These requirements vary with technology, depending on the nature of the improvisation. For example, an emerging trend in material characteristics may require a R&D drive toward in-depth understanding of general material behaviour and phenomena necessitating large R&D input, while the acquisition of a familiar, mature technology in the system may merely require an interfacing design. The risk associated with the development of an individual technology must be determined before the formulation of technology strategy. Its qualification aims to describe one aspect of radical innovation uncertainty: that of R&D risk [Goforth 1999].

Experts in the field under consideration should be involved in determining R&D risk associated with developing technological ability up to the required level. With limited information available on the possibility of reaching the required technological performance levels, forecasting methods like the Delphi method, limit analysis and trend correlation can be introduced toward the allocation of these risk levels. The Delphi Method is an established, systematic interactive forecasting method that recognises the value of expert opinion, experience and intuition and allows using the limited information available, when conclusive scientific knowledge is lacking [Wikipedia 1 2007]. Limit analysis relates the proximity of current performance status to an absolute limit; in trend correlation one technology is a precursor to another and therefore predicts its arrival [Meredith and Mantel 1995].

Table 3-2 is presented to distinguish five levels of R&D risk. R&D risk is defined as the probability of R&D *not* achieving the results aimed for; low R&D risk indicates a higher probability of achieving preferred results; high R&D risk may require major input before achieving good results. In radical innovation the risks of achieving user-required goals are typically high and demands patience from the innovator.

## 3.9 Conclusion

MOT theory and tools are introduced to expand the framework presented by SE through viewing technology as the functional elements of engineering endeavour. Uncertainties, as are typically associated with radical innovation, are characterised by gaining insight into technological attributes and maturity thus providing insight toward well founded strategy formulation. Several MOT tools are introduced to characterise and classify technologies in order to determine their position in the technology landscape. A technology scan familiarises the current system with its technological environment and surrounding landscape. Technology roadmapping provides structured, dynamic techniques for planning technology development support and long-range technology strategy. Technology foresight investigates future technological trends. Technology trend curves are introduced for estimation of technology maturity, prediction of its growth and the determination of R&D risk. Finally, technology strategy techniques are introduced utilising the insight gained into technologies, thus providing assistance for well founded decision-making.

Table 3-2. Definition of R&D risk.

| **Risk level** | **R&D effort needed to achieve sought result** |
|---|---|
| Very low | Minor: little extra resources demanded; mere design problem |
| Low | Some: some resources demanded; integration research problem |
| Moderate | Moderate: fair amount of research resources demanded |
| High | Significant: significant research resources demanded |
| Very high | Major: long-term dedicated research resources demanded |

MOT is an emerging scientific field. Several texts classifying MOT tools and visual aids are emerging [Walsh 2004, Phaal et al. 2005] as ‘integrated sets of management tools and processes underpinned by well-founded conceptual frameworks’ [Phaal et al. 2005]. Future contributions may expand the MOT approaches and tools introduced in this chapter.

The previous and current chapters provided SE and MOT approaches to systematising radical innovation. The next chapter develops the Radical Innovation Methodology as a synthesis of the contributions of SE and MOT.

# CHAPTER 4

# THE RADICAL INNOVATION METHODOLOGY

This chapter proposes a generic formulation of the RIM. The argument for “systematising radical innovation through synthesis of existing theory into a basis for strategic decision-making” (thesis statement from section 1.2) to form a pragmatic methodology is given in this chapter. The uncertainties in radical innovation are comprehended using SE principles; required functionalities are identified and their uncertainties characterised through the description of technological building blocks using MOT insight. The RIM is formulated as this argument. Each phase is introduced and discussed through a breakdown of the principles and typical tools contributing to its procedure. Reference to the organisational roles required for execution of the RIM is provided.

[Note: Where the RIM development refers to previous sections, reference is provided in brackets. The subsections of section 4.1 are denoted according to the five primary phases of the RIM, e.g. block 1 in Figure 4-1 is discussed in section 4.1.1, block 2 in section 4.1.2, etc.]

## 4.1 Formulation of the Radical Innovation Methodology

The RIM is graphically represented in Figure 4-1. The colour codes depict source theory as follows: red blocks are derived specifically from the systems analysis process, orange blocks are derived from SE theory while blue blocks are derived from MOT theory.

The central row depicts the primary phases of the RIM of setting up a reference case (marked with a “1” in Figure 4-1) which is subsequently broken down into its functional systems hierarchy to identify technological elements (2) deployed in the system. These technologies are independently augmented or introduced to form alternatives for evaluation of their impact on system performance (3). Critical technologies are isolated for subsequent assessment of their characteristics, trends and R&D risk (4), thus to provide information to, in conjunction with the information on potential performance impact, set up a strategy (5) toward realising the radical innovation. These procedures are facilitated by the technology manager. Input is provided by the board who is responsible for strategy specific guidance (top row), and the technology experts, who contribute technology specific insight and data during the RIM procession (bottom row).

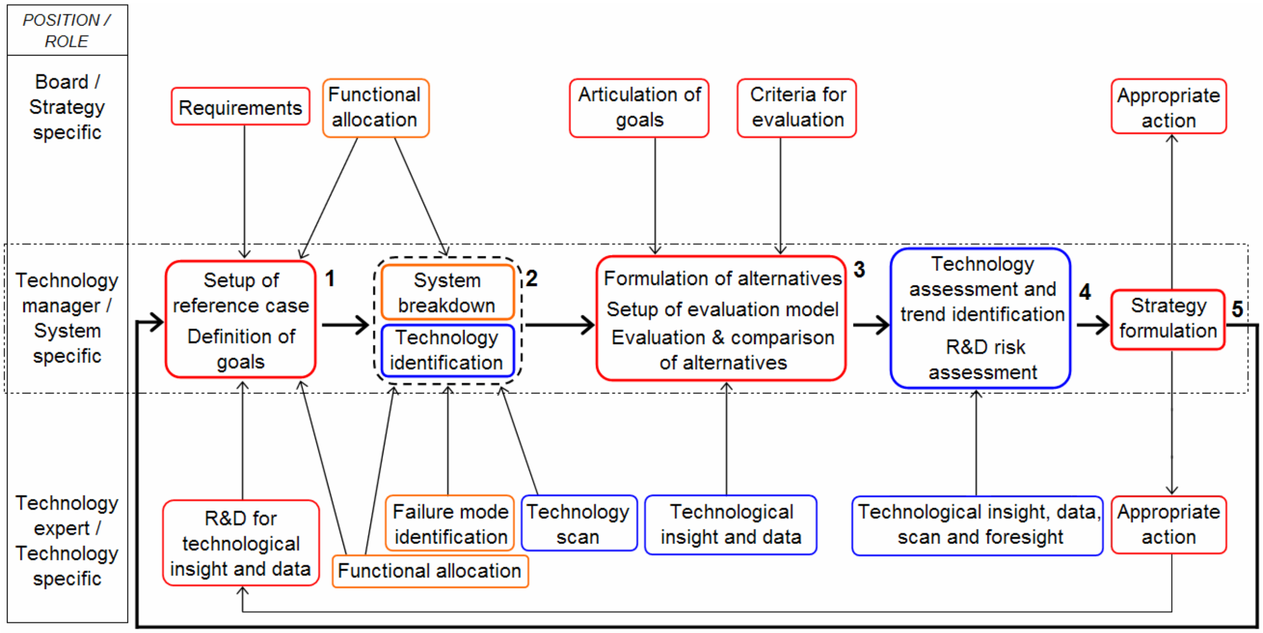


Figure 4-1. Graphical representation of the RIM.

### 4.1.1 Set up of reference case

The RIM commences with the articulation by the board of radical performance requirements and functionality in the form of general qualitative or semi-quantitative requirements.

A reference case solution is synthesised by technical and systems experts based on *current* technological capability and insight into the problem. Decisions about what is included in the reference case must be made with an understanding of the governing and preferred functionalities, failure modes, evaluation criteria and potential technology acquisitions. Being the subject of radical innovation, the reference case may be a non-feasible system. It only needs sufficient description to provide the technology manager with an understanding of conceptual functionality before entering the RIM cycle. Consider the following historic case as validation: National Aeronautics and Space Administration (NASA) did not possess the technology to “land a man on the moon and return him safely to Earth” at the start of the Apollo Space Project [Murray and Bly Cox 1989]. Available technological capability was synthesised into an altogether insufficient system in terms of the project objectives; the system *was* sufficient to identify critical functionality requirements that were subsequently developed to realise the *radical* objective.

All subsequent development in the current RIM iteration is performed in relation to this reference case.

### 4.1.2 System breakdown and identification of technologies

The technology identification phase provides the critical shift in R&D focus from parametrical, optimising design improvement – as is typical of incremental and dramatic innovation – to the functional perspective that is essential for solution of radical innovations. The technology identification phase of the RIM involves the breakdown of the reference case into its systems hierarchy (section 2.4) as far down the levels as is deemed necessary to reveal its intrinsic functional components. This functional breakdown asks the questions: *what* functionalities are required of the system and subsystems and *how* do they achieve these functionalities. Generally, functionalities to resist, mitigate or circumvent extreme actions at any given phase throughout the system life cycle are required. Failure mode identification provides the system breakdown with a comprehensive list from which insufficiencies in the design can be identified and addressed through added functionality. Technology scanning (section 3.4) identifies technologies that adhere to allocated functionality and mitigate identified failure modes.

An iterative procedure with communication between the functional allocation, failure mode analysis and technology scanning is required to define all functional elements of a complete system hierarchy (section 2.4.4); Figure 4-2 illustrates this relationship toward re-articulating the reference case from a technology perspective – a technology tree portraying the company technologies in order for them to identify and understand technology flow and pro-actively develop R&D roadmaps.

### 4.1.3 Evaluation and comparison of alternatives

<u>Formulation of alternative solutions</u>

The RIM evaluation and comparison phase determines the potential of *technologies* to impact system performance. Alternative solutions do not constitute mere design variations but are intelligently chosen technological variations of the reference case. A sensitivity approach investigating the system behaviour with variation in parameter values is not sufficient to determine the behaviour of a system under radical technological innovation (section 1.1.2).

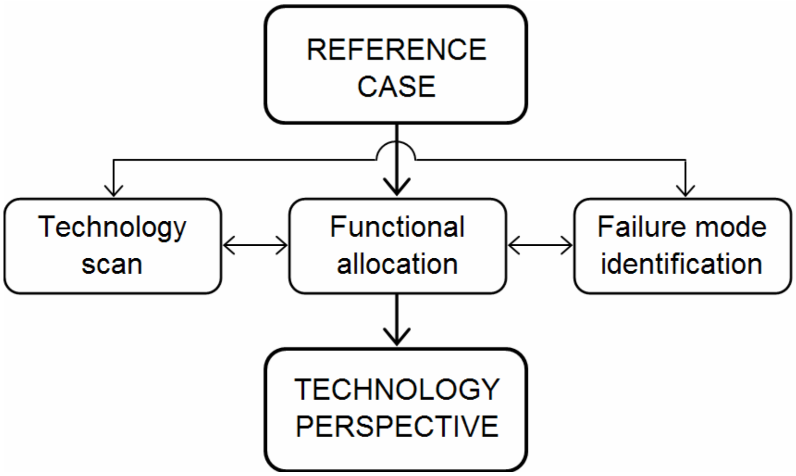


Figure 4-2. Intercommunication between functional allocation, failure mode identification and technology scan yields the technology perspective.

While parametrical studies *do* register sensitivity to system attributes they *do not* allow for determination of the potential of newly introduced functionalities/technologies comprising different sets of parameters. This phase of the RIM incorporates the system performance evaluation process of incremental innovation, as set out in the systems analysis process (section 2.6.2). The radical innovation perspective presented in the RIM, however, requires introduction of new technological functionality or the augmenting of technology performance variables up to preferred values rather than reverting to incremental, more realistic values.

Each technology identified in the previous RIM phase is acquired or augmented and individually integrated with the reference case to yield a list of solution ‘alternatives’. The degree of augmentation is chosen in concurrence with envisioned technical capability (with input from technology experts) and the goals now expressed as quantitative, functional, criteria-based technical performance measures. Note that in the case of radical innovation, goals are predominantly radical and the augmented reference case may not readily attain to it. In the case of the technology being new to the system (i.e. not a parametrical augmentation) the impact of its addition to the system is studied.

Technologies may be augmented by the virtual probing principle – the preferred outcome – (refer to section 2.5.1), not being realistic by normative performance standards. This provides insight on how a system responds *if* a technology could reach the virtually augmented state of performance. Technology trend analysis could subsequently comment on the realism of the particular virtual probing.

### Set up of evaluation model

An evaluation model is set up in response to evaluation criteria specified by the board, making sure that all significant performance attributes of the system are accommodated (section 2.5.2). In radical innovation the model must remain flexible as knowledge of governing functionalities, failure modes and performance criteria introduced in new technologies may shift the focus of the problem solution. Where the evaluation model of incremental innovation evaluates performance in terms of standard limit state equations, radical innovation requires a more accommodating model in case technologies from differing fields, with differing governing parameters and equations, are presented. Decisions during radical innovation should be based on the envisaged benefits of the preferred state of performance of the technology and the potential resulting market size.

Multi-criteria decision-making methods (briefly mentioned in section 2.5.3) could provide decision-making models that capture overall performance trends in response to technological changes.

### Evaluation and comparison of results

Data is gathered to determine the response of each augmented/introduced technological alternative to the various criteria. It is entered into the evaluation model and alternatives are evaluated and compared. Alternatives that hold the most potential are identified, distinguishing the technology portfolio into a spectrum ranging from core to peripheral technologies. Strategically critical technologies are separated for entrance into the technology assessment and trend identification phase. Note that although this filtering to identify critical alternatives could be implemented to maximise resources the entire technology portfolio must be considered during strategy formulation and further iterations because of the possible change of governing aspects of the concept.

The radicality and magnitude of technological endeavour required to achieve user defined goals can be grasped during this phase by keeping the radical requirements and goals in mind. Progress can be measured against these requirements.

### 4.1.4 Technology assessment, trend identification and research and development risk

This phase of the RIM provides approaches and tools for handling the functional uncertainties identified in the technology identification phase. In incremental innovation codified procedure and field theory provide sufficient insight for the development process; radical innovation does not have this luxury – the uncertainties are functional in nature and not necessarily parametrical. Technologies identified to hold significant potential to improve system performance are assessed in terms of their technological attributes and growth trends; technology trends are also identified to establish growth tendencies and maturity of the technology. The R&D risk associated with development of an individual technology must be assessed before the formulation of technology strategy.

#### Technology characterisation and classification

The critical technologies are characterised (section 3.3.1) and classified (section 3.3.2) with the aid of the MOT tools to gain insight into the inherent attributes of internal technologies and their relative proximity to other technologies in the technology landscape. Technology scanning could identify similar technologies; their benefit and acquisition must be considered (section 3.4).

#### Technology trend identification

Technology trends are investigated to determine which technologies promise the most potential for increasing system performance. A technology that is emerging or growing contains inherent potential and must be distinguished from mature or aging technologies that do not promise significant breakthrough contributions (section 3.6.1). If technologies that are critical to the system are mature the prospect of scanning for younger substitution technologies could be considered.

Technology foresight methods aid technology trend identification; it could be particularly integral in radical innovations by aiming to predict future trends, thus pro-actively, strategically engaging future problems with radical solutions (section 3.5). Foresight by multi-disciplinary experts could qualify the probability of a technology actually growing at the determined direction and rate.

The Cascade of Technological Trends determines the current level of development of a technology, furthering the technology trend information by predicting the typical future focus for technology R&D.

R&D risk assessment estimates the risk associated with R&D to bring technologies to required performance levels.

### 4.1.5 Technology strategy formulation

The strategy phase of the RIM considers all alternative evaluation data and technological knowledge from the previous RIM phases. Where, during incremental innovation, strategic decisions are made with business sense based on insight into financial models, R&D risk models and short to medium terms time frames, radical innovation decision-making utilises SE and MOT insight gained during the previous chapters. This provides knowledge and insight into potential performance improvement of the system as well as into the potential of realising required technological performance levels.

Knowledge of the impact of technologies on system performance combines with knowledge of the potential for and probability of technological improvement to integrate into a knowledge basis for strategising an optimised radical innovation R&D roadmap. The functional, technology-based perspective on radical innovation guides board decisions through a systems perspective and insight into the potential of the technology portfolio. Consequent technology priorities are articulated to the R&D facilities of the company through re-allocation and prioritisation of resources for further R&D and subsequent re-introduction to the system (section 3.7).

During the formulation of technology strategy, interaction with several non-technical parties, such as financial executives or investors, require efficient communication of technological information. This can be achieved through the active visualisation of results (section 3.7) and use of common terminology (section 3.3.1) for their comprehension of technology-based business or problem solving potential.

## 4.2 Radical Innovation Methodology dynamics

### 4.2.1 Insight, not rules

The RIM does not propose a series of rules to be followed painstakingly in order to determine the optimal radical innovation R&D path, but should primarily be used as a means of gaining insight into the system and potential for its improvement. The methodology can be customised or re-configured to be optimally applicable to specific radical innovation projects. The RIM does not necessarily result in discrete results and strategy, merely providing insight into system technologies; technologies can often be obscure or indefinable.

### 4.2.2 Repetition and iteration of the Radical Innovation Methodology

The RIM approach and principles, being generically applicable, could be repeated or incorporated in the radical innovation design process as often as is deemed necessary, refining the solution and subsequent strategy with every iteration. As uncertainty diminishes more detailed functionalities, corresponding technologies and criteria are sought [Blanchard and Fabrycky 2006] up to the stage where the R&D is manageable through established incremental innovation frameworks.

Iterative implementation of the RIM approach makes for an improved understanding with each cycle. The insight in one RIM iteration may spark insight in other aspects of the system – in complex systems, where technologies form part of an integrated whole, understanding one technology brings forth understanding of another.

During radical innovation, funding has to be justified and secured for the next iteration development cycle. The RIM could be applied to strategically motivate such project funding.

### 4.2.3 Educated guessing in radical innovations

Resources for technological R&D are limited; hence, conclusive information on radical innovation issues is not always available. In radical innovations, where ideas may be too radical to be acceptable in standard academic publications, one sometimes has to resort to expert opinion and intuition to gather data on a technological subject. This may be unpublished, unofficial information.

### 4.2.4 Generic applicability of the Radical Innovation Methodology

The RIM, being defined as a generic methodology, could be customised for numerous other radical innovations, for example linking a computer and a human brain or even a managerial challenge like HIV/AIDS management efficiency. The functional, problem-solving perspective on innovations, proposed by the RIM, takes a step back to identify the problem-system or the system of which the problem forms a part. Gaps and uncertainties are delimited from the functional systems breakdown and functions required for addressing these gaps are stated, answering “what” nature of functionalities are required to ensure success. The impact of augmented or ideal performance improvement of the uncertainty is evaluated to identify critical elements in the system. These elements are characterised and classified in terms of broader, related elements. They can be assessed in terms of their potential for realising the sought improvement by investigating the potential of developing their current state up to the sought, preferred state. Strategy is formulated by integrating the ideal improvement measures and the potential of realising these ideals; a priority list of critical technologies is set up. Resources are re-allocated to address the development of critical functionalities.

The author is of the opinion that the functionality perspective proposed by the RIM could encourage decision-makers faced with any radical challenges to rethink problem solution from a functional, problem-solving focussed perspective. This could replace the incremental, relative perspectives that results in incremental, relative results that are often used during innovation.

## 4.3 Critical role-players during the Radical Innovation Methodology

Technology managers, the company board and technology expert roles are differentiated in this section to illustrate their critical interaction during the RIM. Figure 4-1 depicts these three levels as differentiating technology managing (systems oriented (central row)), board (strategy related (top row)) and technology expert (technological detail related (bottom row)) events.

### 4.3.1 The role of the technology manager

The technology manager facilitates the five core phases of the RIM as they are stipulated in the introduction to section 4.1. His main role in the RIM entails establishing a systems perspective on the innovation in order to identify functional gaps; and the subsequent investigation toward filling in these gaps through application of MOT. The technology manager is not an expert in any specific technological field; his expertise lies with the technology management processes, having a perspective on understanding systems and overviews. Note that the technology manager is not necessarily the project champion, i.e. the person responsible for commitment and drive to realise radical solutions, but merely facilitates the RIM. The technology manager is trained in MOT methods thus performing the assessment and trend identification phases of the RIM in conjunction with experts. A summary of all relevant technological information can be compiled containing visualisations for presenting information. This provides the board with a comprehensive systems and technological perspective on radical innovations; hence efficient strategy can be formulated.

The technology manager possesses skills that enable the gathering of data concerning the phases of the RIM. He must know to ask the board and technology experts questions that are strategically aimed at acquiring adequate, relevant, useful data for efficient incorporation into the RIM phases to highlight critical aspects and issues of the radical innovation.

The extensive focus on and use of tools available to the technology manager may hinder the flow of the RIM while essential, governing technological characteristics still run the risk of passing by undefined, uncomprehended or un-recognised. The focus of the technology manager must rather be to aim to understand the system and the synthesis of its technologies through the optimal implementation of appropriate techniques and tools. The technology manager must consult expert knowledge instead of aiming to understand every technical aspect of the radical innovation; expert insight remains the most invaluable and efficient source of technological and systems comprehension.

The board trusts the technology manager to diffuse the company strategy into R&D priorities [Roussel et al. 1991]. Technology experts work closely with the technology manager, trusting him to represent their capabilities and the technology development status in the boardroom.

### 4.3.2 The role of the board

The board is responsible to deliver the requirements baseline for reference case synthesis. These requirements provide insight in the functionalities and technical performance measures needed to realise the radical innovation. Furthermore, it provides information on the evaluation criteria as specified by the user for incorporation in the evaluation model. Upon receiving information on technology evaluation, comparison, assessment, trend and R&D risk, the board plays an integral role in the formulation of strategy, aligning technology potential with the priorities of the company. Resources are then re-allocated according to technological priorities.

### 4.3.3 The role of the technology expert

The technology expert serves the technology manager and the radical innovation with specific technical insight and contribution. R&D is performed to formulate a representative reference case. Close conference with the technology manager is critical in order to incorporate all governing facets for user satisfaction as specified by the board. Functionality and failure mode information is provided for the setting up of the systems hierarchy and technology tree. Further, the proximity of the technology expert to the technology field and peripheral landscape leaves him the best equipped to perform a technology scan in search of similar or substitute technological solutions. During the technology assessment and trend identification phase, the technology manager and expert collaborates to gather data for the description of each critical technology. R&D risk is described by the expert in the particular technology. After strategy formulation the technology expert receives and diffuses the re-allocation of resources and R&D focus, developing technologies toward an improved next iteration reference case.

## 4.4 Conclusion

This chapter introduces and formulates the RIM, concluding Part I of the dissertation. It distinctly discusses each phase of the RIM showing how it applies to systematising radical innovation and characterisation of its uncertainties and required functionalities. Technology managers, the company board and technology expert roles are differentiated, illustrating their critical interaction.

A *theoretical* solution to the argument of the thesis as stated in section 1.2 is formulated. A systematic approach to form a basis for strategic decision-making in radical innovation is synthesised from established SE and MOT theory.

Part II of the dissertation commences in the next chapter. It aims to provide *validation* of the premise of the RIM through its application on the Solar Chimney Power Plant chimney structure, i.e. to formulate R&D strategy for radical innovation of the chimney toward realisation.

# PART II

# VALIDATION OF THE RADICAL INNOVATION METHODOLOGY – APPLICATION TO THE SOLAR CHIMNEY POWER PLANT CHIMNEY STRUCTURE

# CHAPTER 5

# SOLAR CHIMNEY POWER PLANT CHIMNEY BACKGROUND, CONCEPT AND SHORTCOMINGS

*"Therein is the tragedy. Each man is locked*
*into a system that compels him to increase his*
*herd without limit—in a world that is limited."*
*- Garrett Hardin*

With the turn of the millennium mankind is faced with immense challenges. Global crises range from famine and water shortage to sanitation and pandemics to energy wars. *Climate change* – a major 21st century global challenge – is the term circumscribing the actions and symptoms of a planet in disequilibrium. The actions: significant irregularities in global and local climate patterns. The symptoms: tremendous economic loss [Stern 2006], famine and human death. The cause: non-sustainable development [IEA 2003].

But every challenge presents an opportunity. Mankind must think outside the confines of incremental, relative, standardised problem solution; he must radically innovate. Massive breakthroughs should be realised in order to stand up to these challenges, to present pro-active, outside-the-box, sustainable solutions to relieving misery, preserving Earth and saving human lives.

This chapter proposes the Solar Chimney Power Plant (SCPP) as one potential solution – a technology for generating clean electricity. The SCPP comprises a solar collector, turbines and a chimney of significant dimensions; only with an economy of scale may the plant achieve current market competitive costs. The proposed height for the chimney of 1,500 meters, places it far outside current Structural Engineering norms. Radical innovation is required.

The chapter commences with a formulation of the incentive for clean energy generation, stipulating the requirements for a solution. The SCPP is introduced as a potential solution and a conceptual design within constraints of current engineering knowledge and capabilities – but with significant uncertainties – is proposed as a reference case for application of the RIM. Uncertainties in the design and theoretical background are identified and related to the ideal solution, hereby grasping the extent of the required innovation.

## 5.1 A contemporary context for radical innovation

The following section provides the context from which the drive for greatly improved system functionality (standard or non-standard and radical) ensues. Global and South African incentives for the innovation of clean energy technologies form the context from which requirements for its efficient innovation are formulated. These create a favourable environment for radical innovation.

### 5.1.1 Climate change and global energy trends

Climate change and the demise of oil

The global phenomenon of climate change, said to be caused partially by excess Greenhouse gas[i] (GHG) emissions from human activity [IEA 2003], is causing an increasing number of irregularities in climate patterns leading to various adverse effects including human death, famine and immense economic loss [Stern 2006]. Critics of climate change ascribe its phenomena to the fluctuations that are perceivable throughout Earth's history [An Inconvenient Truth 2006]. *Whichever way, mankind is to pursue a sustainable relationship with his surroundings – erratic consummation of the Earth's resources is not sustainable and cannot be pursued as standard behaviour* [(based on) Hardin 1968]. Various mitigative measures including policy adaptation, realisation of economic mechanisms and public awareness aim to reverse the adverse impact of human activity.

An associated shock to global economies is the actual diminishing of oil resources as predicted in literature [Grove 1974, Deffeyes 2005], believed to be a driving force behind soaring, fluctuating prices of oil markets over the past years[ii] [Renewable Energy World 2007]. The world is "addicted to" [US State of the Nation address, 2006] a resource that is, almost daily, becoming more expensive.

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[i] Greenhouse gases are components of the atmosphere that contribute to the "greenhouse effect". An excess of these gases is the main activator of adverse climate change [IEA 2003].

[ii] During the final stages of compiling this document (early 2008) the oil price in the United States had risen to more than five times its value at beginning 2002.

## Sustainable energy generation and clean energy ethics

Climate change and ramping oil prices are gradually shifting the focus of global planners and technologists toward more efficient, conserving, sustainable ways of generating and managing energy [Deffeyes 2005]. Furthermore, poverty stricken countries lack domestic energy generation while energy supplicating technologies are key to their upliftment from the "trenches" of limited access to economic opportunity, education, information and healthier livelihoods [United Nations 2005, Schlaich 1999]. Dealing with energy in a sustainable manner testifies of a long-term, *stewarding* relationship with the Earth – a truly sustainable approach toward maintaining ourselves, our neighbours and our surroundings.

## Growth in the renewable energy industry

Environmentally aware energy markets are desperate for sustainable, economically viable energy solutions but economic inertia strain the immediate inception of renewable energy technologies. The cheap[iii] energy technologies generally have high pollution levels while clean energy technologies are generally expensive. In spite of their relatively high costs several clean energy technologies are emerging through a global energy "market pull" due to increasing environmental awareness. Increasingly large investments for capacity installation, R&D to decrease the cost of clean energy technology and formulation of supporting policies are observed globally. More than $66Bn was invested in 2007 in new renewable energy capacity worldwide (see Figure 5-1), up from $30Bn in 2004 [Renewable Energy World 2007]. Proponents of solar thermal electric technologies predict around 300% decrease in generation cost within the next 15 years. Half the cost reductions are based on performance R&D but the other half is attainable through scaling-up to larger plant sizes and volume production effects [Pitz-Paal et al. 2003; Schlaich 1999; Mail and Guardian 2008a]. This can boost renewable energy technologies to a state of competitiveness with conventional energy generation technologies.

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[iii] Note that the cost of conventional energy production appears low because it seldom incorporates consequential life cycle costs such as pollution and environmental degradation; more realistic, long-term models include these costs yielding higher values.

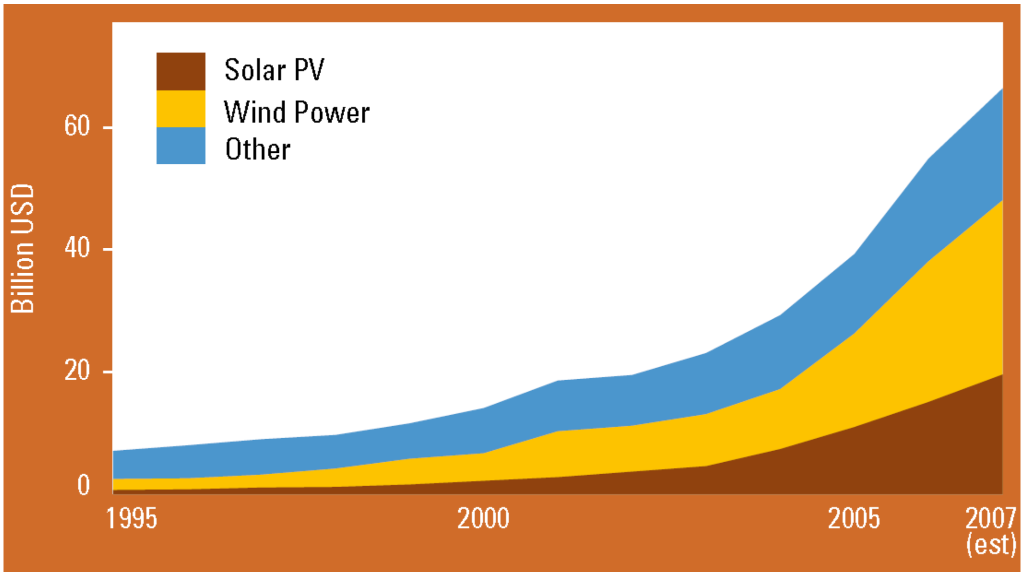

Figure 5-1. Annual investment in renewable energy capacity (excluding large hydro), 1995-2007 [Renewables 2007]

### 5.1.2 South African energy and renewable energy trends

Energy demand and emissions footprint

South Africa has the highest energy consumption per capita in Africa with a very high reliance on the non-renewable, coal, which is used for over 92% of the electricity generated [DME 2003, Banks and Schäffler 2006]. Although South Africa is only the 27th largest world economy based on gross domestic product [World Bank 2006], its per capita GHG emissions are amongst the ten highest in the world [Parker and Blodgett 2007].

The South African power utility, ESKOM, states in their Annual Report 2006 [ESKOM 2006] that the South African government posited growth target of 6% per annum require an augmentation of existing national capacity by 2,000 MW per annum over the next 20 years. Early in 2008, however, electricity blackouts were experienced due to a *shortfall* of approximately 3,000 MW delivered power [Mail and Guardian 2008b]. Projections show that ESKOM could run out of excess base load[iv] by 2010.

As a developing country, South Africa has not made a formal commitment to reducing emissions below current levels as had several developed countries signed under

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[iv] Base load is the steady capacity of power supply regardless of total power demand, the latter being accommodated by "peak load". Running out of base load implies permanent electricity shortage (not only during peak demand).

the Kyoto Protocol [UNFCCC 2003]. It is anticipated that pressure from governments, civil society and consumers of South African goods will grow and persuade South Africa to commit to GHG reduction targets inducing economic incentive to invest in clean energy technologies. Together with energy shortages this challenge presents significant opportunities for energy diversification through the implementation of renewable energy technologies.

### South African renewable energy resource, industry and targets

South African wave and wind energy resources are moderate compared to the best sites in the world while the solar resource in the north western regions of the country rank amongst the highest in the world [DME 2003] (Figure 5-2). Although solar energy currently contributes insignificantly to the national electricity pool one South African energy scenario predicts solar thermal electric technologies to contribute almost 25% of the domestic energy generation pool by 2050 [Banks and Schäffler 2006].

In anticipation of pressure on the national power generation capability and the global push toward clean energies, the South African government set a target of 10,000 GWh of electricity to be produced by renewable energy by 2013 [DME 2003] including the installation of solar thermal electrical power plants with a total capacity of 300 MW [NER 2004].

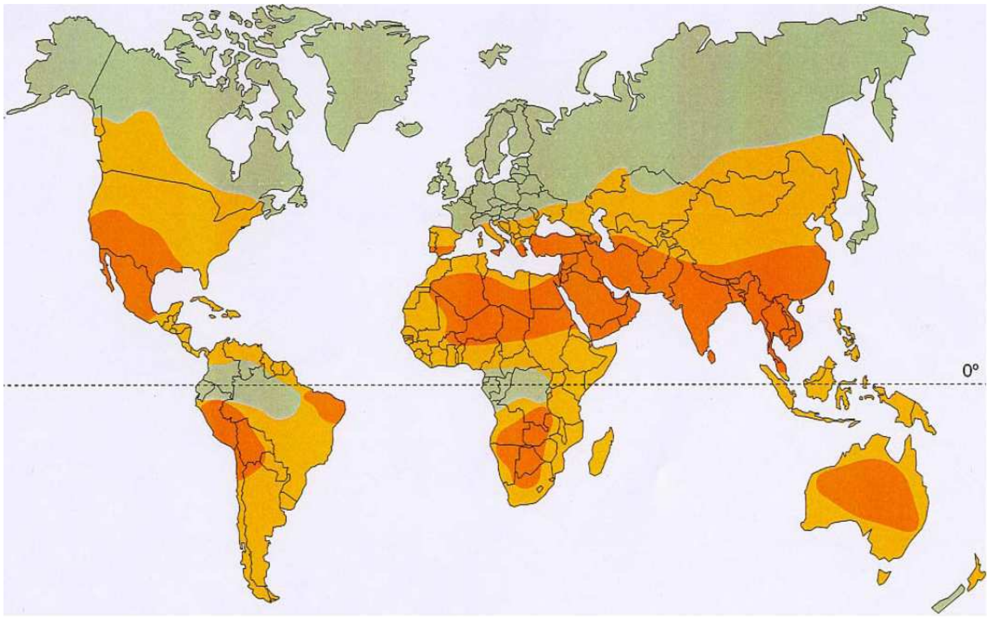

Figure 5-2. Global solar radiation [Solar Millennium 2004].

### 5.1.3 An incentive for radical renewable energy technology innovation

These ethical and economical issues (discussed in sections 5.1.1 and 5.1.2) are creating incentive for ventures outside normative design. Familiar, incremental innovation practice is found limiting or depleted – inadequate to provide the measure of change required to mitigate ensuing challenges. It does not deliver a sufficient approach for managing progress to accommodate the developmental jumps demanded to mitigate the challenges. Engaging radical innovation, with its higher threshold of uncertainty, can be motivated more easily. Uncertainties that were previously perceived as intolerable are now engaged, being motivated by the greater return on investment (or even necessity) that the realisation of radical innovations promise.

Pressure to generate clean energy and the global oil-based energy crisis presents unprecedented opportunities for the development of alternative energy generation technologies. *Clean, non oil-using, cost-effective* solutions are sought. Where, previously, extensive innovation of these “new” functionalities was overlooked in the light of economical performance, the drive for their realisation can now be justified.

Significant political and economical drives for clean energy innovation are currently present in most countries, also South Africa, cultivating environments for radical innovation. The global renewable energy industry is expectant for radical breakthroughs to “change the game” (refer to section 1.1.1) of the global energy industry in the next decades.

The RIM is applied on one such a radical clean energy concept – the SCPP. A systematic approach to the radical innovation is needed to overcome its immense structural and costing challenges. This may elevate the concept to a prime candidate for harnessing the clean energy provided by the sun.

## 5.2 The Solar Chimney Power Plant chimney reference case

The SCPP is a solar power plant that produces clean energy and does not need a continuous supply of cooling water [Schlaich 1995] making it a unique “cluster” energy generation technology since solar radiation rich regions often suffer from water shortage. It could contribute to mitigation of the climate change crisis if developed up to a state of structural integrity and financial feasibility.

### 5.2.1 Chimney operating principle and required dimensions

A SCPP system, illustrated schematically in Figure 5-3, consists of a transparent circular collector system, typically from glass or plastic, supported relatively low above the ground surface. Central to the collector is a tall chimney system with a power conversion unit located at its base. Solar radiation penetrates the collector roof and heats the ground beneath which in turn heats the adjacent air. Hot air rises through the central chimney driving turbines which generate electricity [Schlaich 1995].

An economy of scale applies to the SCPP. The energy generating performance of the system greatly depends on the magnitude of the dimensions of the chimney because the driving force that causes air to flow through the system is a function of the pressure difference between a column of cold air outside and a column of hot air inside the chimney [Pretorius et al. 2004]. The energy output of the power plant increases exponentially with increase in chimney size – see Figure 5-4. A 1,500 meter tall chimney yields three times the energy of a 750 meter tall chimney annually.

Over the history of the SCPP several proposals were made with regards to its optimal dimension configuration, mainly based on estimations by Schlaich et al. [2004b]. More recently Pretorius [2007] published design sheets that provide energy output for various power plant dimensions.

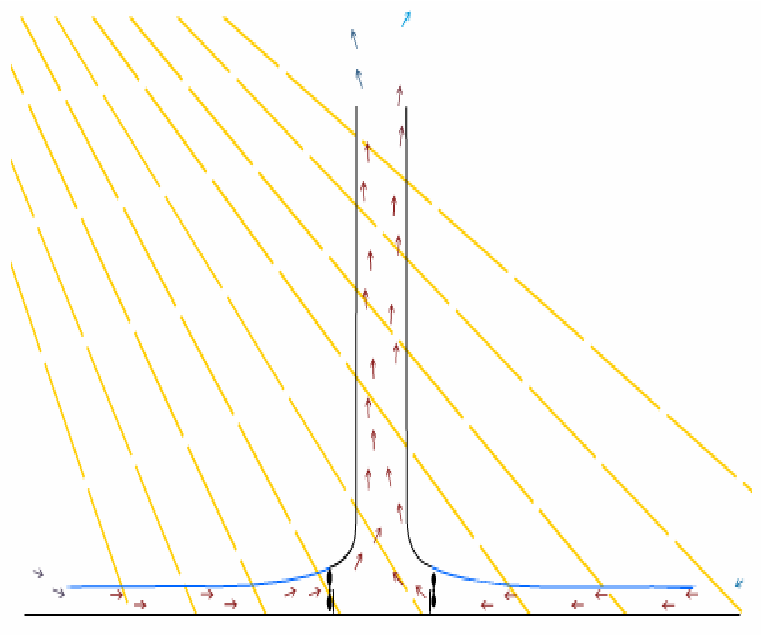

Figure 5-3. Schematic representation of the SCPP [Schlaich 1995].

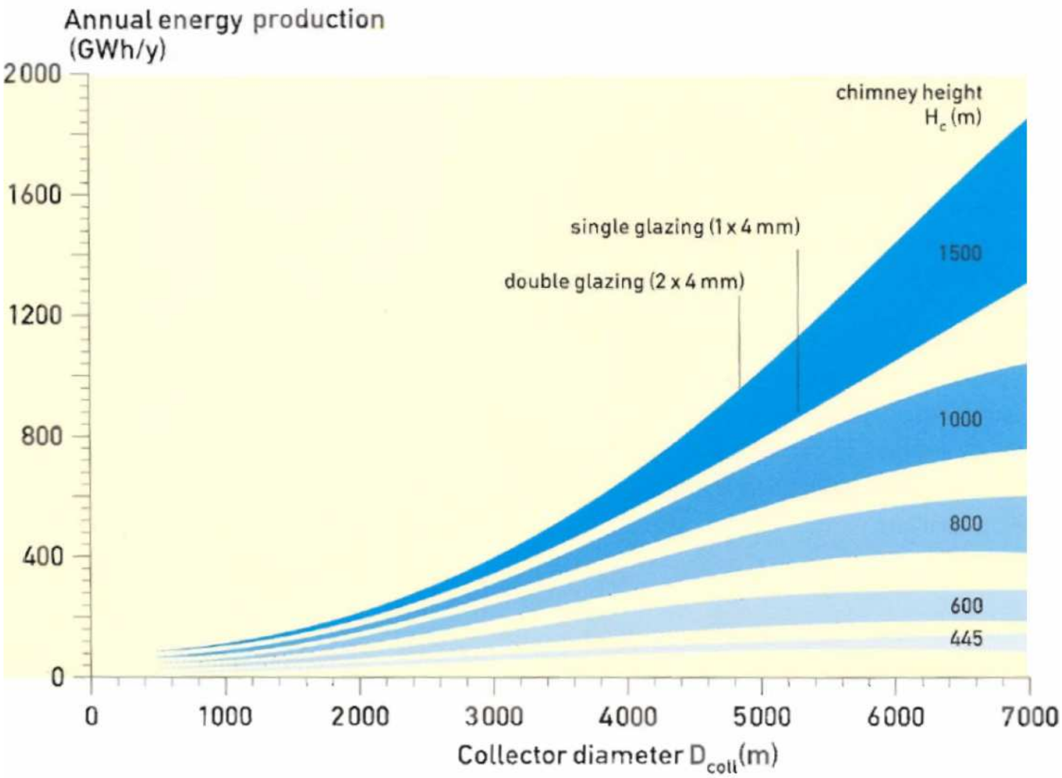

Figure 5-4. Annual energy production by the SCPP for various plant configurations [Schlaich 1995].

A demand for an output of 200 MW peak generation capacity was proposed for the design of a SCPP to be situated in the sun-rich Northern Cape, South Africa [Stinnes 1997]. The proposed geometry of this SCPP system comprises a 6,900 meter diameter collector with a 1,500 meter tall chimney shell, 160 meters in diameter[v] [Van Dyk 2004]. These output values and dimensions express semi-quantitative requirements governing early conceptualisation.

### 5.2.2 Reference case set up

The reference case is chosen in the midst of R&D activity; hence it is difficult to determine which R&D state is the best representation of a typical chimney structure. The range of conceptual proposals for the solution of the chimney is summarised and background

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[v] The dimensions provided here, and that was also used in the Van Dyk [2004] study, are based on unpublished correspondence with the University of Stellenbosch Solar Chimney research group during early stages of research on the SCPP performance. Recent research results show these dimensions to yield peak power of 275 MW [Pretorius 2007]. Schlaich [1995] predicts a much higher peak.

for the choice of reference case is provided. The reference case is subsequently chosen. Geometry and actions for the reference case are specified based on knowledge available at the time of reference case synthesis.

Conceptual proposals in realising the chimney

A *chimney* is defined as “a vertical flue that provides a path through which air or smoke is carried away” [Webster 2008] implying the realisation of a sustained through-flow channel. The SCPP requires a simple, large diameter hollow cylinder that is not particularly slender and subject to very few user demands in comparison with inhabited buildings [Schlaich et al. 2004b]. A few concepts are proposed for fulfilment of this definition.

Schlaich et al. [2004b] proposes a freestanding reinforced concrete chimney as the optimal solution and mentions guyed tubes with corrugated metal sheet walls and cable-net designs with cladding or membranes as alternative concepts.

Another concept, the Floating Solar Chimney, comprises successive aluminium-supported balloon rings, inflated with a lighter-than-air gas (NH3, He) making the structure buoyant. It promises a chimney height increase by a factor of three, increasing peak power output by 350%, and a significant decrease in cost [Papageorgiou 2004]. This concept is not wind-resistant but deflects significantly under strong winds. Energy generation capacity decrease temporarily, but as the wind subsides the structure and energy yield return to its normal state.

The Atmospheric Vortex Engine concept [Michaud and Michaud 2006] replaces the chimney functionality by the centrifugal force of a vortex of warm buoyant air manufactured by ‘steam injectors’. The vortex height could extend into the lower troposphere (10-15 kilometers) resulting in a high plant efficiency. The solar collector is replaced by naturally heated surface air. Dismissal of both the chimney and collector structures decreases costs substantially.

Note that no concepts of significant height have been realised; a 200 meter tall, cable stayed, metal sheet chimney was constructed as a SCPP pilot plant in 1981/82 [Schlaich et al. 2004a].

A choice must be made from the array of concepts as well as variations within the concrete concept.

### Background for the choice of reference case

The concept that is characterised the most thorough at the stage of determination of reference case is chosen in order for the RIM to start with less uncertainty than other concepts would contribute. The reference scientific context is preferred within roughly familiar boundaries to allow useful, illustrative application of the RIM and less diversion to acquisition of expert knowledge. (Technology experts instigate technology acquisition but their expertise is gained through significant resource expenditure, something that this study cannot hope to emulate. Only limited expert resources were available. These had to be used sparingly and efficiently, in this case, on validating the RIM rather than solving the SCPP problem. Note that this does not imply that acquisition of radical technologies was not considered in this application.)

The reference case entering the loop of the RIM, being the subject of radical innovation, may be a non-feasible system (section 4.1.1). Being a radical innovation it still requires significant technological improvement to achieve a state of feasibility.

### The choice of chimney reference case

The concept solution chosen in this dissertation is limited to that of the self-supporting reinforced concrete structure, as is utilised by Schlaich [2004b]. The reinforced concrete concept, as it is currently defined, is not a feasible solution by conventional Structural Engineering standards [based on Van Dyk 2004]. The other concepts are dismissed because of high uncertainties associated with their unfamiliar (to the author, who partially fulfilled a role as an expert in this study) technological environment in order to remain within more familiar technological boundaries. This enables the current RIM application to draw off South African expertise and resources (Note that although South Africa also has a well established steel industry, steel-based SCPP chimney concept(s) was not investigated up to the commencement of this study; hence it was decided to remain within the *more* familiar technological environment.).

South Africa has an established reinforced concrete industry and academic fraternity. Numerous thin shell reinforced concrete chimneys have been constructed in the country. South African industry is well connected to international expertise in this field. Furthermore, the reinforced concrete concept would presumably be cheaper in South

Africa than the higher technology steel-net, cable, membrane and vortex concepts due to higher acquisition and construction costs required by these higher tech concepts.

Thus the RIM application and validation – the priority subject of Part II of the dissertation – need not be distracted by resources spent on familiarisation with technology specific issues but can be enhanced by convenient access to technological information and proximity to cutting edge technology.

Knowledge base during reference case set up

A knowledge basis based on interaction with Structural Engineering experts and completed introductory research further support the reference case that is proposed in this chapter.

Commercial secrecy forced the University of Stellenbosch Institute for Structural Engineering (US-ISE) to engage independent research on the chimney with the only guidance contained in publications by long-time developers of the concept, Schlaich Bergermann und Partner [SBP 2004, Schlaich 1995, 1999 and Schlaich et al. 2004a, 2004b]. Publications state structural feasibility of the chimney based on the introduction of circumferential cable stiffening, “bicycle wheel” systems at several levels inside the chimney to stabilise the structure and reduce material volume. Schlaich concludes that “perhaps the spoked wheels [*the bicycle wheels*]... are the only really new feature of solar updraft towers [*SCPP’s*] compared to existing structures” [Schlaich et al. 2004b].

A scoping study on the chimney structure [Van Dyk and Van Zijl 2002] identified key areas for further research[vi]. Follow-up research addressed the chimney-foundation interaction [Van Dyk 2004, Van Dyk and Van Zijl 2004], the study of dynamic effects of the chimney [Rousseau 2005, Harte and Van Zijl 2007] and mitigation of resonance inducing behaviour [Alberti 2006, Harte and Van Zijl 2007, Van Dyk et al. 2006]. Measures for the improvement of the structural performance [Schindelin 2002, Sawka 2004, Alberti 2006] and cost [Van Dyk 2004] were proposed, including circumferential and longitudinal stabiliser configurations. Reinforcement placement, wall thickness re-configuration [Lumby 2003], the circumferential stiffening structures [Lourens 2005],

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[vi] Erratum: In Van Dyk, C. & Van Zijl, G.P.A.G. (2002) *Solar chimney: improving the concept*, Proceedings for International Association for Shell and Spatial Structures Conference in Warsaw, Poland, June 2002: the first global eigen-mode is reported to occur at 0.3133 Hz. This value is erroneous and should be 0.1 Hz.

thermal loading on the chimney shell [Nel 2005] and cable stayed chimney stiffening [Fraser 2006] were also investigated in introductory R&D efforts.

Of this research some conclusive results contribute to the reference case. Inconclusive research, having been identified and characterised (although only in part) by technology experts, can be incorporated as technology alternatives in the RIM. The US-ISE research adds much insight into the mechanisms surrounding the chimney but several major issues remain to be addressed. The structural feasibility claim made by Schlaich et al. [2004b] is yet to be confirmed being subject to the major uncertainties that constitute the radicality of this concept.

### Reference case geometry

The proposed chimney geometry is based on collaborations (of which some results are unpublished) between the US-ISE and the Bergische Universität Wuppertal Statik und Dynamik der Tragwerke (BUW-SDT) in Germany.

The chimney comprises a 1,500 meter tall, 160 meter diameter chimney tube constructed from thin shell reinforced concrete. The reference case location, on which all climate and action data is based, is chosen as Sishen, a mining town in the Northern Cape, South Africa. A dimensioned illustration of the chimney reference case also depicting the approximate geometry and location of the circumferential stiffening systems (bicycle wheel ring stiffeners) is provided in Figure 5-5a together with the chimney-to-foundation transfer system (Figure 5-5b) and a section through this transfer system (Figure 5-5c). The cylindrical reinforced concrete shell starts from an elevation of 125 meter (as seen in Figure 5-5c) to allow for optimal air through-flow area below this. It extends to the tip, elevated at 1,500 meter above ground level. The cylindrical shell thickness decreases linearly from a thickness of 1.95 meters at 125 meter to 0.3 meters at 1,000 meter elevation from where it remains constant up to the tip. Axial and flexural forces are transferred to soil level through 36 fin-like structures (Figure 5-5b) connected to 36 columns directly below the shell. The solid cylindrical reinforced concrete columns stand 350 meter tall and are 10.7 meter in diameter; the fin-stiffeners stand 350 meter tall with a toe length of 160 meters at ground level and a width of 2 meters. Six circumferential stiffening systems are placed at regular 220 meter intervals from the chimney top, i.e. at 400, 620, 840, 1,060, 1,280 and 1,500 meter elevation (see Figure 5-5a).

The proposed foundation structure consists of 18 rectangular reinforced concrete beams, each 160 meters long, 0.5 meters broad and 2.5 meters deep, supporting each fin and column.

The Finite Element Method (FEM) model based on this geometry and used for numerical analyses in this study is presented in Appendix A.

Actions

The main actions working on the chimney are gravity and wind load. Operational and maintenance load associated action is considered to be negligible. The proposed region for the implementation of the SCPP shows negligible seismic action; hence no earthquake effects are included in the reference case. Research on the effects of thermal action on the 1,500 meter tall chimney [Nel 2005] determined that the impact of the extreme thermal load case is small relative to the gravity and wind action (a numerical analysis determined it to contribute to approximately 0.04% of the overall buckling factor); damaging thermal cracking in concrete is assumed to be resisted by detail reinforcement design.

The wind loading model used in the reference case is provided in detail in Appendix B. A gravity acceleration of 9.81 meters per second squared is assumed. The change in this value due to an elevation of 1,500 meter is negligible.

## 5.3 Definition the Solar Chimney Power Plant chimney development as radical innovation

With the reference case defined, this section provides quantitative and qualitative descriptions of its shortfall and uncertainties relative to an ideal (feasible) structure, thereby providing a measure of its radicality. During the initial phases of the RIM, qualitative performance measures are specified. In the SCPP chimney case these measures constitute the need for clean, non-oil based, cost-effective energy generation for South Africa. Re-articulated in terms of the SCPP concept quantitative performance measures are specified. A peak power output of 200 MW requires a 6,900 meter diameter collector and a 1,500 meter tall, 160 meter diameter chimney.

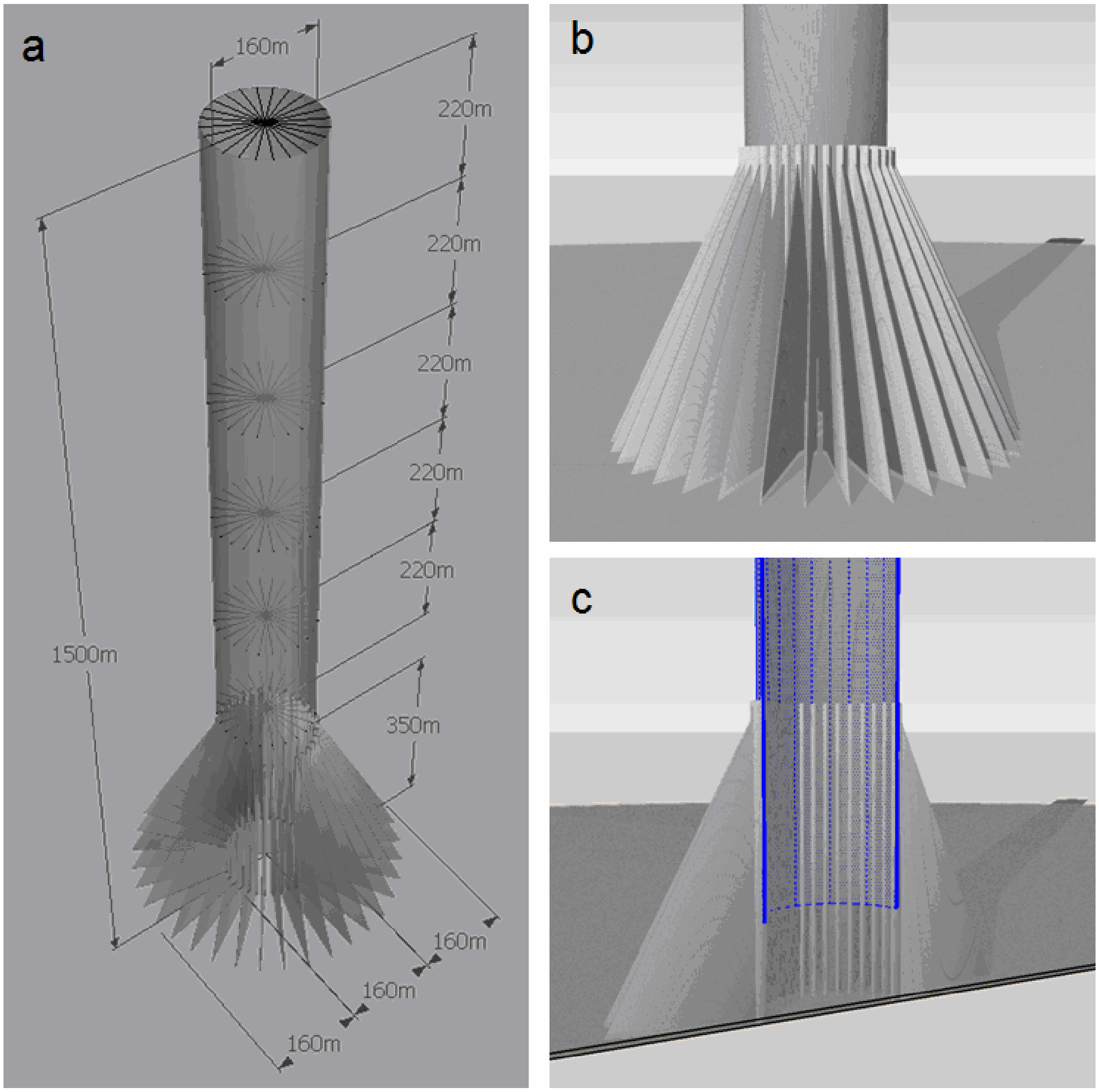

Figure 5-5. a) Dimensioned illustration of the chimney. b) transfer-to-foundation system. c) chimney cylinder depicted in blue construction lines.

The currently proposed SCPP chimney, synthesised from standardised theory and practice, presents significant shortfalls from entering the market for economically competitive energy generation technologies. Current practice fails in delivering the sought levels of performance improvement. The investigation *beyond* these standard technological levels – radical innovation – must be engaged to break through to higher levels of user satisfaction. The current section (section 5.3) investigates the radicality of the structural behaviour of the reference case proposed in section 5.2.2, i.e. a description of the main uncertainties from a structural perspective. It is also compared to trends of realised structures in industry. Its electricity costs are compared to those of South African and international power utilities.

A perspective on what is required of the radical innovation provides rudimentary goals for the first iteration RIM toward achieving feasibility. More detailed quantitative descriptions can be defined in response to functional technological goals as they are identified during the technology identification and evaluation phases of the RIM, and in further iterations. Detailed shortcomings in the design and theoretical background must be identified at these further stages and related to the ideal solution, hereby delimiting and quantifying uncertainty in the innovation in increasing detail.

### 5.3.1 Structural challenges

SCPP chimney specific uncertainties and shortfall

The 1,500 meter tall SCPP chimney concept presents several major technical uncertainties. Knowledge and insight into these form an important guide to structural realisation. The main uncertainties in scientific theory are:

- The applicability of the current mathematical formulation of a *wind extrapolation model*.
- The uncharacterised *local wind direction variations* over the height of the tall structure [Rousseau 2005].
- Wind around the chimney almost always enters the *trans-critical flow regime* due to its large diameter and the relatively high wind velocities. This flow regime is under characterised due to physical limits in experimentation leading to uncertainty in determination of the dynamic wind action on the chimney [Alberti 2006].
- The *cross wind force spectrum* is an integral parameter in the estimation of structural response to the cross wind excitation. Its values vary greatly with the building aspect ratio and the level of turbulence in the approach flow. It is currently only characterised for square and rectangular cross sections but remains to be characterised for circular cross sections.
- *Buckling* in column structures are prevented by design against a critical buckling factor which is taken, in the case of conventional cooling tower design (a similar

> cylindrical thin shell structure), to be equal to 5 [VGB 2005]. This factor is used when simplified analysis is performed, as opposed to more realistic and accurate nonlinear stability analysis, considering finite strains. It was calibrated to be safe for cooling towers, while allowing use of a generally available analysis method. Such calibration has not yet been done for the SCPP; hence the applicability of the design guideline to the SCPP chimney is uncertain.

These fundamental, theoretical uncertainties are typical of radical innovations and necessitate exhaustive familiarisation with the technological environment of the innovation. Note that in radical innovation official references may not necessarily be available because of the radical, often intuitive, “non-academic” postulations prevalent in radical thinking.

Physical shortfalls in the structural performance are quantified by determination of buckling and frequency response values (refer to Appendix A for more information on the models used for these numerical FEM analyses and to Appendix C for the structural evaluation model developed later in this RIM application). By performing a linear elastic buckling analysis of the chimney under gravity, peak gust wind (a 1,000 year return period wind applies – refer to Appendix B, section B1) and internal suction load (comprehensively reported in Appendix G) the first critical buckling factor of 1.63 is computed. This shows a *significant shortfall* from the stated critical buckling factor of 5.

Frequency response analysis describes how a structure, given its material and geometrical characteristics – and, hence, its free vibration frequencies – transmits and responds to dynamic excitation. Holmes [2001] describes the *gust load factor* analysis, a method determining a quasi-static factor for application on the along wind overturning moment [Australian Standards 1989] exerted on a structure (refer to Appendix C, section C2 for the validation of the use of this method). Uncertainties in the applicability of this method to the SCPP chimney warrant the use of a 2,000 year return period[vii] in calculating the reference wind for application in this method. The ideal result is assumed as the result from application of a 500 year return period wind; a 1,000 year return period wind is used in the buckling analyses (refer to Appendix B, section B1), but it is estimated that with adequate experimental testing (characterising actual wind

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[vii] A 2,000 year return period is associated with structures that are essential to post-disaster recovery or associated with hazardous facilities in [ISO DIS 2007].

phenomena) reliability of the chimney frequency response could be reached for a 500 year return period wind. Under these conditions an ideal result gust load factor of 1.50 applies. The analysis parameters and results are reported in Appendix C2. The reference case gust load factor of 1.513 (Appendix G, section G2.1) does not far exceed the ideal gust load factor. Although, for this criterion, the reference case performs close to the ideal and can be designed according to standardised practice, it must remain represented because it exemplifies the basic structural integrity of the system and may be adversely affected by other technology introduction.

Constructability presents major uncertainties in realising a tall structure such as the SCPP chimney. Only recently, with the construction of the 800 meter tall Burj Dubai was concrete pumped above 600 meters [Putzmeister 2007]. Further, the chimney reference case requires large volumes of building materials, for example, 25 times more concrete than the Millau Viaduct which is the tallest bridge in the world and has a total length of 2.46 kilometers. Materials may not be readily available and its transport and handling may be logistically challenging.

Further uncertainties include those contributed by modeling “new” technological concepts and project management and financing. A RIM process-specific uncertainty concerns the difficulty of setting up a model for chimney evaluation not knowing whether acquired technologies may change behaviour completely and present new sets of failure standards and functionality to subsequently be characterised and incorporated in the RIM.

### Civil Engineering structures

Civil Engineering structure systems are inherently prone to uncertainty. Structural projects are typically once off and have long time-frames and large budgets compared to the repetitive nature in the manufacturing sector where optimisation and automation is possible. One of the primary functionalities of civil engineering structures is the resistance of long return-period extreme loads, requiring them to have very high levels of structural reliability – there is no room for uncertainty, especially not for the significant uncertainties (that cannot be mitigated by standardised design practice) prevalent in radical innovation.

A brief look at current limits in ultra-highrise structures and cooling towers provide a grasp into the magnitude of technological scaling required from “normal” Civil

Engineering structures toward the realisation of the SCPP chimney. The Petronas Towers in Kuala Lumpur, at 452 meters, the 101 storey Taipei 101 in Taiwan, at 509.2 meters and the Burj Dubai, at a height of approximately 800 meters (construction to be completed in 2008/9) as well as several other ultra-highrise structures are pushing the boundaries of conventional design and construction. High-tech technologies enable dynamic stability control systems and breakthrough construction methods. Still, thin shell reinforced concrete cooling tower stacks, portraying similar shape and basic structure as the proposed reinforced concrete SCPP chimney, have only recently reached heights of 200 meters [Harte et al. 2007].

The 1,500 meter height of the SCPP chimney is far beyond the normative heights of similar structures but rumoured future projects indicate a development drive toward taller structures with plans for buildings of 1,852 meters (Al Jabar tower, Bahrain), 1,022 meters (Murjan Tower, Bahrain) and 1,001 meters (a tower in Madinat al-Hareer, Kuwait) [Wikipedia 2 2008].

### 5.3.2 Cost requirements

Energy costs of the reference case, when related to average market costs, provide a further indication of the measure of radical innovation required in the SCPP chimney to reach a state of feasibility.

<u>Current and realistic SA electricity cost</u>

SA electricity costs are of the lowest in the world [Engineering News 2007a]. The levelised electricity cost[viii] (LEC) provided by the SA electricity utility range from R0.18/kWh (reported for the year ending 31 March 2007 [ESKOM 2007]). The national electricity utility stated that prices are “unsustainably low” due to its basis on historic costs [Finance 24 2005]. Costs will be increased annually by more than 18% [Engineering News 2007a] to accommodate for significant capacity expansions in the next decades [Engineering News 2007b]. Early in 2008 ESKOM opted for a price hike of 53% [Mail and Guardian 2008c]. As an indicator of international electricity costs comparison, the 2004 cost of electricity for industrial clients in Brazil (comparable to the

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[viii] Levelised electricity cost indicates the averaged cost per kilowatt-hour of electricity over the life time of the project, i.e. including construction, fuel, operating and maintenance costs. Electricity costs are calculated as for February 2008.

developing SA economy) and Japan of R0.35/kWh and R0.92/kWh, respectively [Australian government 2006], can be considered, showing the SA electricity cost to be relatively low.

Note that cost models used by industry often do not include contemporary life cycle costs like pollution tax, that are due to increase the LEC of fossil fuel power plants, or additional revenue from "carbon credits" and government feed-in tariffs that could greatly impact the financial feasibility of clean energy technologies in the future.

In the light of the above described fluctuation and modeling inaccuracies used for determination of life cycle energy cost, a value of R1.00/kWh is considered as the base reference cost (ideal result) in this dissertation.

SCPP electricity cost

The reference SCPP installation cost is an estimated R31.44Bn, resulting in a LEC of R8.65/kWh[ix]. Appendix D expands the cost model and associated assumptions. Significant cost reductions are required to decrease the SCPP costs to the assumed state of market competitiveness of a LEC of R1.00/kWh.

## 5.4 Conclusion on Solar Chimney Power Plant chimney background, concept and shortcomings

This chapter commences the RIM application on the SCPP chimney by an introduction to market requirements. Global and SA climate change and energy crises are presented as a context urgently requiring radical innovations. Clean, non-oil fuel, cost efficient energy production could provide solutions to the challenges stated. These qualitative demands are re-articulated as quantitative requirements and, if met by a 200 MW SCPP concept, comprise a 1,500 meter tall, 160 meter diameter chimney with a 6,900 meter diameter solar collector.

A detailed reference case for this concept is provided as the coalescence of research collaboration between the US-ISE and the BUW-SDT and conceptual background by Schlaich,

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[ix] A publication by Fluri et al. [2006] in which the current author co-authored, reports a LEC of €0.316/kWh which equates to around R3.63/kWh (1€=R11.50 as on 28 February 2008). This significantly lower value occurs because the chimney used in that study had no stabiliser fin stiffener structures which contribute to 80% of the cost of the current chimney system. The current cost model without fin stiffeners yields a LEC of R2.82/kWh. The difference is due to discrepancies in the energy performance models and currency value. Further, a glass roof collector was used in the Fluri et al. study [2006] that accounted for *significant* costs. Also note that the LEC is very sensitive to fluctuations in interest and inflation rates.

Schlaich et al. and Schlaich Bergermann und Partner [Schlaich 1995, Schlaich et al 2004a and 2004b and Schlaich Bergermann und Partner 2004]. The reference case is related to contemporary achievement and norms to understand the measure of radicality relative to the sought performance. All subsequent (first iteration) RIM technology acquisitions are related to this reference case.

Some uncertainties in the SCPP chimney where identified in this chapter. They could, of course, be addressed individually, in an isolated manner. These uncertainties can, however, be placed in a framework from which a functional focus could investigate their criticality for subsequent more focussed and accurate mitigation. In the next chapter the reference case is broken down into its essential technological elements to gain insight into the building blocks and uncertainties of the SCPP chimney system.

# CHAPTER 6

# TECHNOLOGY IDENTIFICATION IN THE SOLAR CHIMNEY POWER PLANT CHIMNEY

The reference case SCPP chimney proposed in the previous chapter enters the next step in the RIM, i.e. the system breakdown and technology identification phase. The chimney reference case, synthesised through current incremental practice and associated theory, was proven to fall short of sought performance levels. In the critical shift of focus presented by the technology identification phase of the RIM, the constraints of conventional design practice are shaken off by engaging the *raison d’être* – the functionality – of the system and its elements.

In the first step, the system is broken down to its essential functional elements through the system functional breakdown. Failure mode identification identifies vulnerable and absent functionalities of the system. Technology scan proposes mitigative and amending technological functionalities from the technology landscape. In re-articulating functionality as technology, a technology tree is presented. Finally, a list of technologies is set up, combining the technology tree and previously identified theoretical uncertainties.

## 6.1 Functional breakdown of the Solar Chimney Power Plant chimney

The functional breakdown engages the system decomposition process by asking the following: *what* functionalities are required of SCPP systems, and *how* do they achieve these functionalities. The reference case is decomposed into its functional hierarchy as far down the system levels as is deemed necessary to reveal its intrinsic functional components. Note that this study concerns the expansion of the chimney system only as it exists during its fully operational phase (assuming that construction is completed and decommissioning had not yet commenced – study scope defined in section 1.6.1, under the first point).

The SCPP system consists of three main subsystems: the collector (denoted with “A” in Figure 6-1), the turbine (“B”) and the chimney (“C”). The collector function ‘collects’ solar heat energy and feeds it through the turbine where its kinetic energy is converted to electrical energy. The pressure differential between the air inside the chimney and the air volume outside provides the driving force causing air to flow through the system (see section 5.2.1).

Section 5.2.2 introduced the SCPP chimney function as a vertical channel for air flow, requiring a simple, large diameter hollow cylinder that is subject to no habitation demands. Any chimney consists of several sub-systems that contribute various functionalities to the system. Figure 6-1 displays these subsystems of the SCPP chimney system: a foundation (denoted by a “1” in Figure 6-1), chimney-to-foundation transfer (2) and chimney tube (3). Each of these is investigated in this section to identify its functionality. Note that the SCPP chimney may also accommodate a diffuser (depending on the choice of turbine configuration) to optimise air flow but its functionality is not structurally interesting; hence it is not considered further. It is, however, important to take notice of every subsystem and component of the system for a comprehensive perspective on the whole.

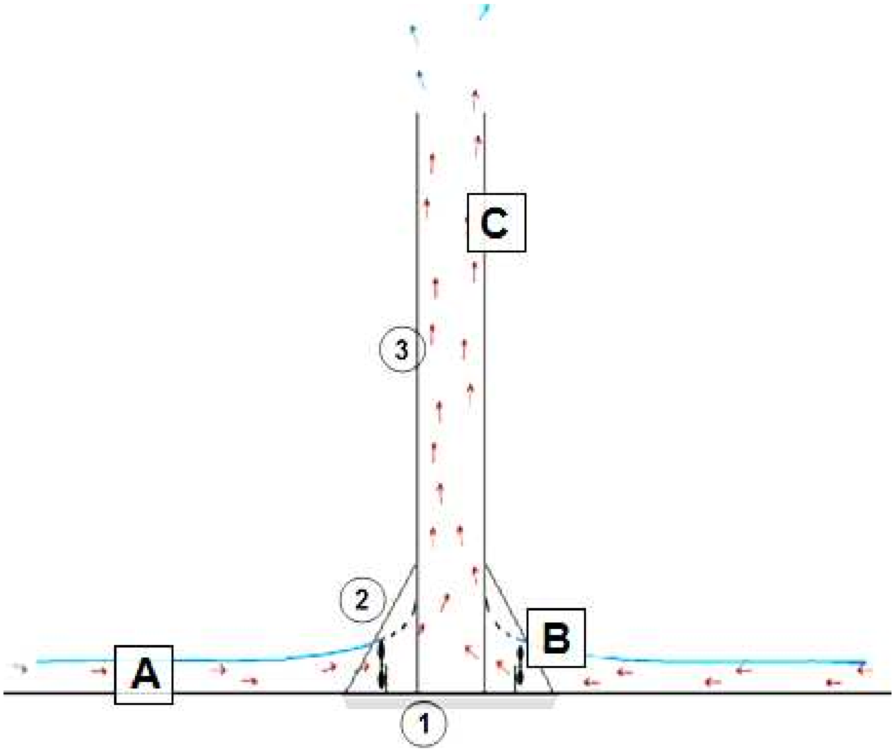

Figure 6-1. Subsystems of the SCPP system (denoted by blocks) and of the chimney system (denoted by circles).

### 6.1.1 Chimney foundation functionality

The chimney foundation system considers subterranean, geological and geotechnical information to present a foundation structure supporting the super-terranean structures. It must present sufficient load bearing capacity for transferral of static and dynamic loads, i.e. compression, tension and shear, to the soil/rock substrates, as well as for fastening and anchorage of super-terranean systems.

The fixity of the chimney, i.e. the degree to which its base support is constrained against translation and rotation, depends on the soil characteristics. In the SCPP reference case the Sishen soil characteristics show sufficient stiffness which, in combination with appropriate foundation design, allow full constraint of the structure against practically all translation and rotation degrees of freedom (refer to Appendix A, section A1.2) for the validation of this assumption), i.e. to support the chimney. Previous research shows that the chimney base could be in tension under extreme static and dynamic wind loading, hence anchorage functionality is required [Van Dyk 2004].

### 6.1.2 Chimney-to-foundation transfer functionality

The chimney-to-foundation transfer structure transfers static and dynamic loads imposed on the chimney tube, as well as its own loads, via the foundation into the soil/rock substrate. The chimney is presented with a functional contradiction between load transferral and the creation of space for air through-flow from the collector and turbines to the chimney. A functional solution that transfers all loads to subterranean systems (through large fin shaped columns) while creating a through-flow channel for the passing air is presented in Figure 5-5b [Van Dyk 2004]. The transfer structure can also support the turbine and its airflow duct configuration.

### 6.1.3 Chimney tube functionality

The chimney tube consists of a large diameter, hollow, vertical channel for air flow. It is subject to gravity and exposed to extreme wind action and must be functional in resisting[i] these loads throughout the life time of the structure. Any obstruction in the air flow channel incur losses, decreasing the energy yielding capacity of the SCPP system. Such obstructions [Van Backström et al. 2003] may include frictional shell surface properties or the

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[i] Actions can also be *accommodated* as with the Floating Solar Chimney concept (refer to section 5.2.2).

circumferential stiffening structures that are currently implemented in the reference case. These stiffeners present another contradiction; creating an optimal through-flow channel while using part of the cross sectional area for structural stiffening. Obstacles in the tube (e.g. circumferential stiffener system) may be aerodynamically shaped to reduce losses [Von Backström et al. 2003].

Apart from physical flow obstructions the air flow channel must be shaped for optimal through-flow conditions, within limits of structural feasibility. A gradual flaring of the chimney inner area with height increase keeps the flow rate optimal [Von Backstrom 2000]. Exit losses occur when the rapidly flowing air inside the chimney meets the relatively stagnant body of air above the chimney [Fluri and Von Backström 2006]. These could be mitigated by an aerodynamically more favourable chimney exit geometry.

Several structural stabilisation systems can be incorporated in the chimney tube system to mitigate or circumvent adverse structural behaviour. Failure mode identification isolates the functionalities required for mitigative measures. The functional–failure description aims to identify failure modes for mitigating design and optimisation of structural performance (remember that failure occurs not only when physical structural limit states are not reached but also when a performance goal is not attained).

## 6.2 Failure mode identification

In Structural Engineering failure mode identification often suffices for the identification of many of the functions necessary in the system; standardised design processes are set up to resist all known failure modes in order to satisfy user requirements. The radical nature of the SCPP chimney, however, warrants a deeper investigation aiming to cover all possible failure modes in the system in a comprehensive, unassuming way thus identifying lacking functionality. All potentially significant perspectives toward critical failure mode identification must be engaged. Two perspectives are used to identify failure modes in the SCPP, i.e. material failure (*apparent* failure cause) and action-based failure (*root* cause of failure).

### 6.2.1 Material failure modes

Ultimate limit state based technical failures in civil structures occur due to material failures, although they are not necessarily the root cause of failure. Local material failure may be the consequence of global effects, for example excessive deformation resulting in local stress concentration causing concrete crushing.

The main materials present in the reference case chimney are concrete, reinforcement steel and structural steel. Table 6-1 presents the prevalent failure modes of concrete, steel and reinforced concrete at the material level.

Table 6-1. Material failure modes.

| Material | Failure mode |
|---|---|
| Concrete | Compression (crushing)<br>Tension (cracking)<br>Shear<br>Fatigue due to repetitive load<br>Material deterioration<br>▪ Carbonation<br>▪ Poor mix (e.g. water-cement ratio)<br>▪ Aggressive environment (chlorine, salt, ice)<br>▪ Alkali-Silica reaction |
| Steel | Plastic yield<br>Corrosion and other aggressive environment based effects<br>Fatigue<br>Brittle tensile failure (high carbon steel) |
| Reinforced concrete | Bond slip<br>Spalling (carbonation/corrosion) |

### 6.2.2 Action-based failure cause

The root causes of failure are generally action based. Various actions on the structure, together with their dynamic interaction, provide perspective on the causes of failure modes. The actions on the chimney were stipulated in section 5.2.2 and Appendix B, section B1. The action based failure modes are reported in Table 6-2. Note that the entries in Table 6-2 are the result from specialist (expert) investigations into SCPP chimney behaviour.

Table 6-2. Failure modes from an action perspective.

| Action | Failure mode |
|---|---|
| **Gravity** | |
| ▪ Axial load | Axial failure due to gravity and wind load |
| ▪ Shearing load | Shearing failure due to gravity and wind load at positions of shear transfer |
| **Wind action** | |
| ▪ Along-wind cantilever pushover | Flexural or shear failure due to total wind induced moment on a section along the chimney height [Van Dyk et al. 2006] |
| ▪ Wind-induced circumferential ovalling | Flexural or shear failure due to total pressure distribution-induced moment on a section around chimney circumference [Van Dyk et al. 2006] |
| ▪ Dynamic along-wind resonance | Failure by resonance. Wind gust frequency spectral density indicates resonance potential due to low excitation frequency [Van Dyk et al. 2006] |
| | Failure by resonance. Impulses in along-wind force brought about by periodic increase in Reynolds-numbers cause sudden, significant fluctuation in the drag coefficient resulting in resonance probability [Van Dyk et al. 2006] |
| ▪ Dynamic across-wind resonance | Failure by resonance. Periodic, alternate vortex shedding produces low frequency alternating transverse force resulting in resonance probability [Van Dyk et al. 2006] |
| ▪ Wind configurations | Localised flexural or shear failure due to wind pressure combinations on a specific surface |
| | Failure by resonance. Excitation of higher modes due to various wind configurations along height and circumference [Rousseau 2005] |
| ▪ Frictional wind forces | Axial or shear failure. Any obstruction to air flow cause frictional forces, e.g. shell surface roughness or obstructions in the inner area |

## 6.3 Technology scan for mitigative, amending and optimising measures

With the chimney failure modes identified, the technology manager and experts scan the technology landscape for mitigative measures to minimise the impact of failure modes on system performance. Improved structural performance is sought through implementation of novel, intelligent manipulation and control of detrimental actions and response in the structure. Note that mainly detrimental *actions* are considered here, but that material based failure modes could also be addressed by scanning the technological landscape for relevant functionality, e.g. a lighter, stiffer material could mitigate bending and structural response modes. The scanning process aims to identify specific functionalities (responding to failure modes identified) for incorporation in the system, thus moving outside standardised design practice by engaging the functional/technological sphere. This is achieved through the utilisation of external devices or adaptation of inherent characteristics like material properties. The detail integration of the identified technologies with the current chimney system, like fastening and design against device failure, are not considered during system synthesis ("black box" components are merely integrated into the system and not developed themselves – refer to section 2.2).

Note that several of these mitigative technologies are already incorporated in the chimney reference system, such as longitudinal stiffening fin stiffeners and circumferential stiffeners.

### 6.3.1 Longitudinal stiffening

In an attempt to decrease global chimney cantilever bending and increase global free vibration frequencies and critical buckling resistance factors, longitudinal stiffening resistance is sought. Trees and industrial towers provide direction to formulating a solution; their lower regions taper to a broader base enlarging the moment of inertia and, hence, the resistance against cantilever bending. The fin stiffeners already incorporated in the reference case (refer to Figure 5-5b for visual representation) are examples of such longitudinal stiffening. Cable stays could stiffen structures by providing additional support.

Longitudinal stiffening can further be achieved through alteration of the chimney geometry, e.g. through the incorporation of parabolic hyperboloid cooling tower shapes (Figure 6-2 – cooling tower geometry incorporated in the SCPP chimney), increase in diameter or wall thickness re-configuration. Geometrical changes must be implemented in close coordination with thermo-dynamical experts as alteration of the through-flow channel geometry has significant influence on the energy production capacity of the system.

### 6.3.2 Circumferential stiffening

Circumferential bending due to the total wind pressure distribution moment around the circumference can be mitigated by circumferential stiffening improving structural performance under static, dynamic and buckling loading. The bicycle spoke wheel concept incorporated for the reference case (refer to Figure 5-5a for visual representation) is an example of a circumferential stiffening technology.

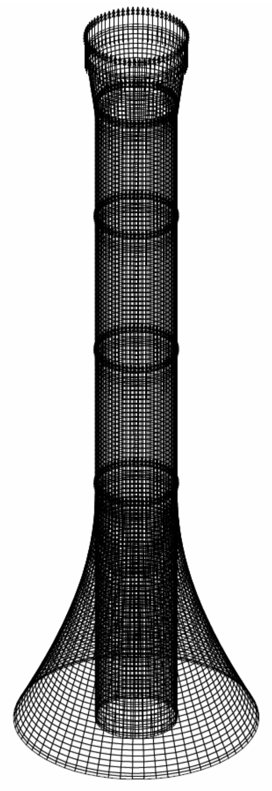

Figure 6-2. Parabolic hyperboloid geometry incorporated into the SCPP chimney [Sawka 2004].

### 6.3.3 External damping system

External damping measures have been in use for more than three decades [Datta 2003]. It involves the addition of a device that reduces structural response to prevent discomfort, material fatigue and subsequent structural failure due to vibration. It reacts to the resonant frequency oscillations of the structure by means of active, passive or semi-active damping systems, e.g. springs, dashpots or pendulums. Many damping devices exist; their impact relies on a thorough understanding of the theory of dynamics and their behaviour in order to efficiently utilise it in the global system.

### 6.3.4 Manipulation of wind–structure interaction

Wind–structure interaction manipulation systems circumvent oscillation behaviour [Holmes 2001, Alberti 2006] caused by periodically separating vortices by warping or distorting adverse air flow and separation. Several wind–structure interaction manipulation technologies exist, e.g. helical strakes, perforated shrouds and spoiler plates located around the upper outer regions of the chimney, as seen in Figure 6-3a) [Kumar et al. 2008] and b) [Internet 1 2008].

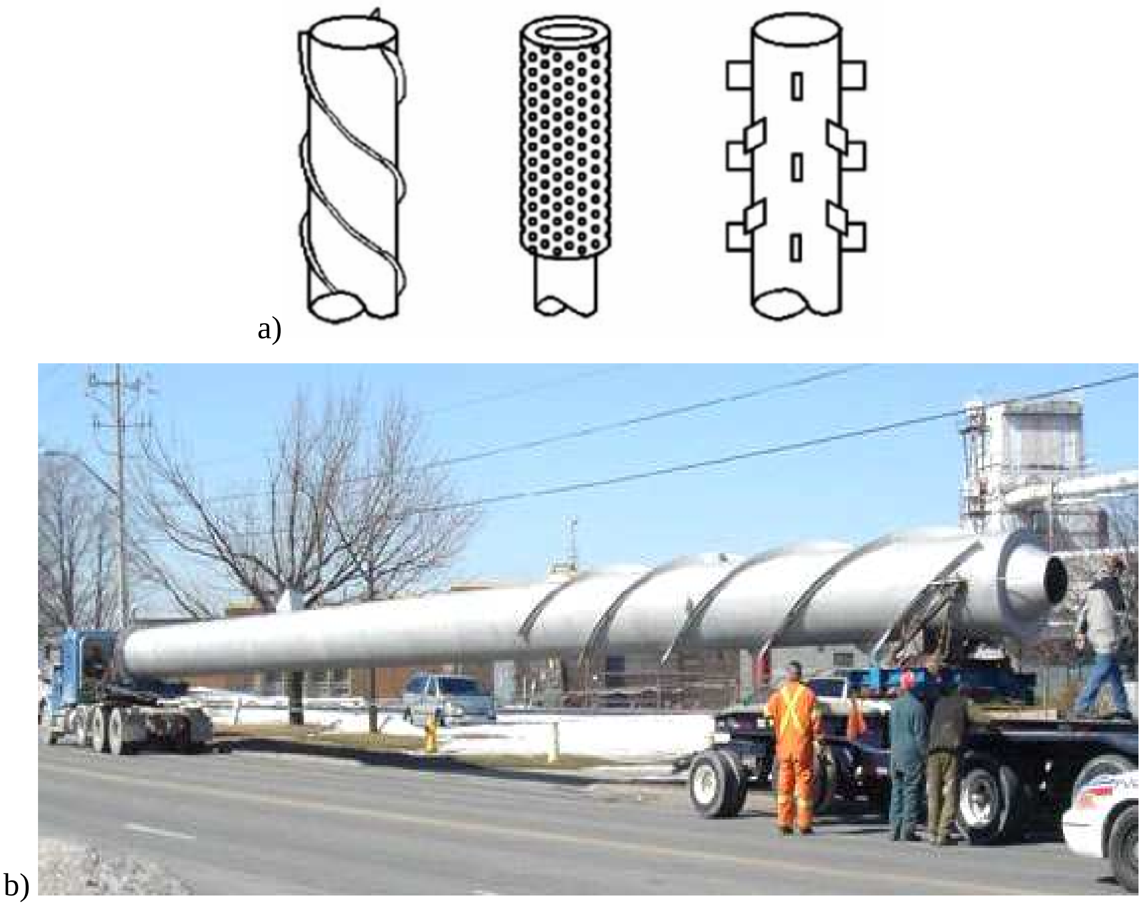

Figure 6-3. a) Systems for the manipulation of vortex induced vibration [Kumar et al. 2008] and b) an example of helical strakes wrapped around the upper third of a chimney stack in transit [Internet 1 2008].

### 6.3.5 Improvement of material characteristics

The improvement or durability of material characteristics directly improve the resistance of a structure to compressive, tensile, flexural, shear and torsional shear loading as well as to material fatigue and deterioration. Furthermore, the inherent damping characteristics of a structure which dictate how a structure responds to harmonic excitation are functions of its geometry and material.

### 6.3.6 Directional design

The notion of designing a foundation only for *directional dependent* wind, as is found in nature with the root systems of trees – only growing into the regions that are experiencing more action – could decrease material volume required and, hence, lower capital costs. The structure is appropriately strengthened only in the regions that resist statistically determined wind-based actions as presented with the aid of a wind-rose (Figure 6-4 presents an example of a wind rose with radial histograms depicting prevalence of wind direction and speed).

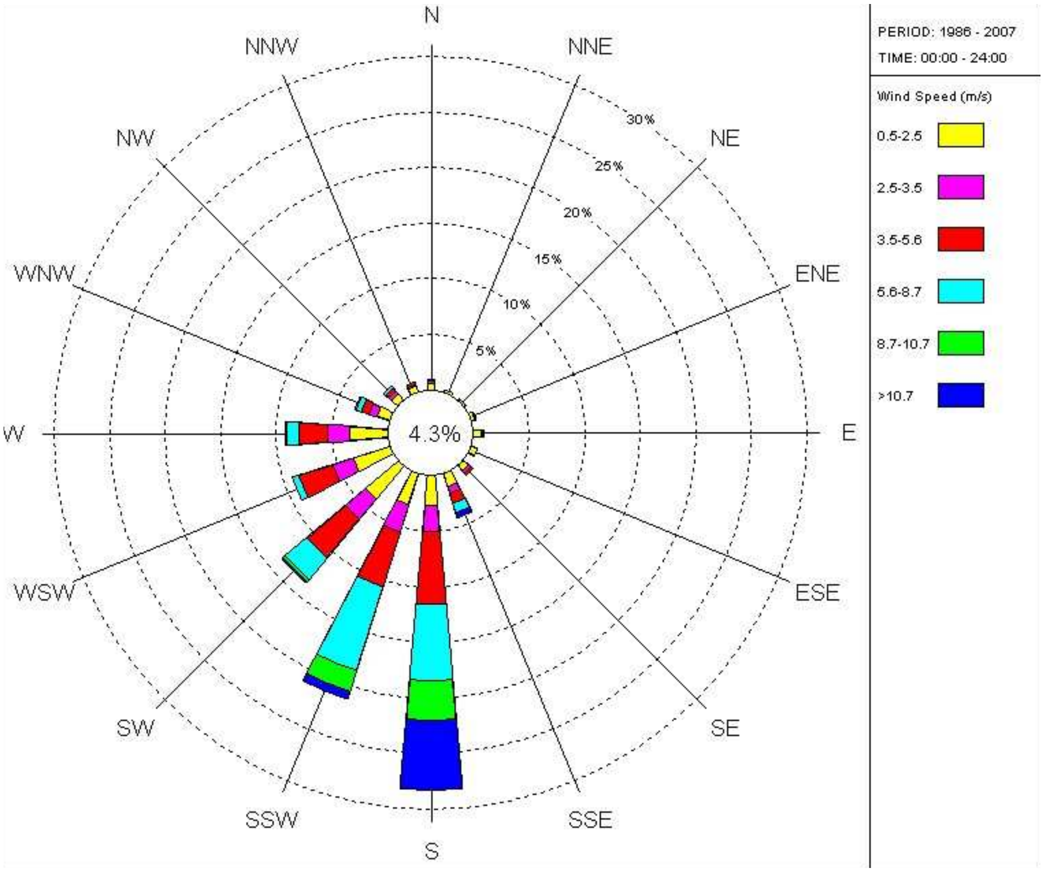

Figure 6-4. A wind rose displays statistical data of prevailing wind directions and speeds [WeatherSA 2007].

## 6.4 Integration of functionalities into a technology tree

A functional technology tree combining all the insight from the previous sections follows in Figure 6-5, providing a comprehensive functional breakdown of the SCPP chimney system. Technologies active in the system can be placed in a comprehensive framework from which gaps can be identified and substitute technologies proposed.

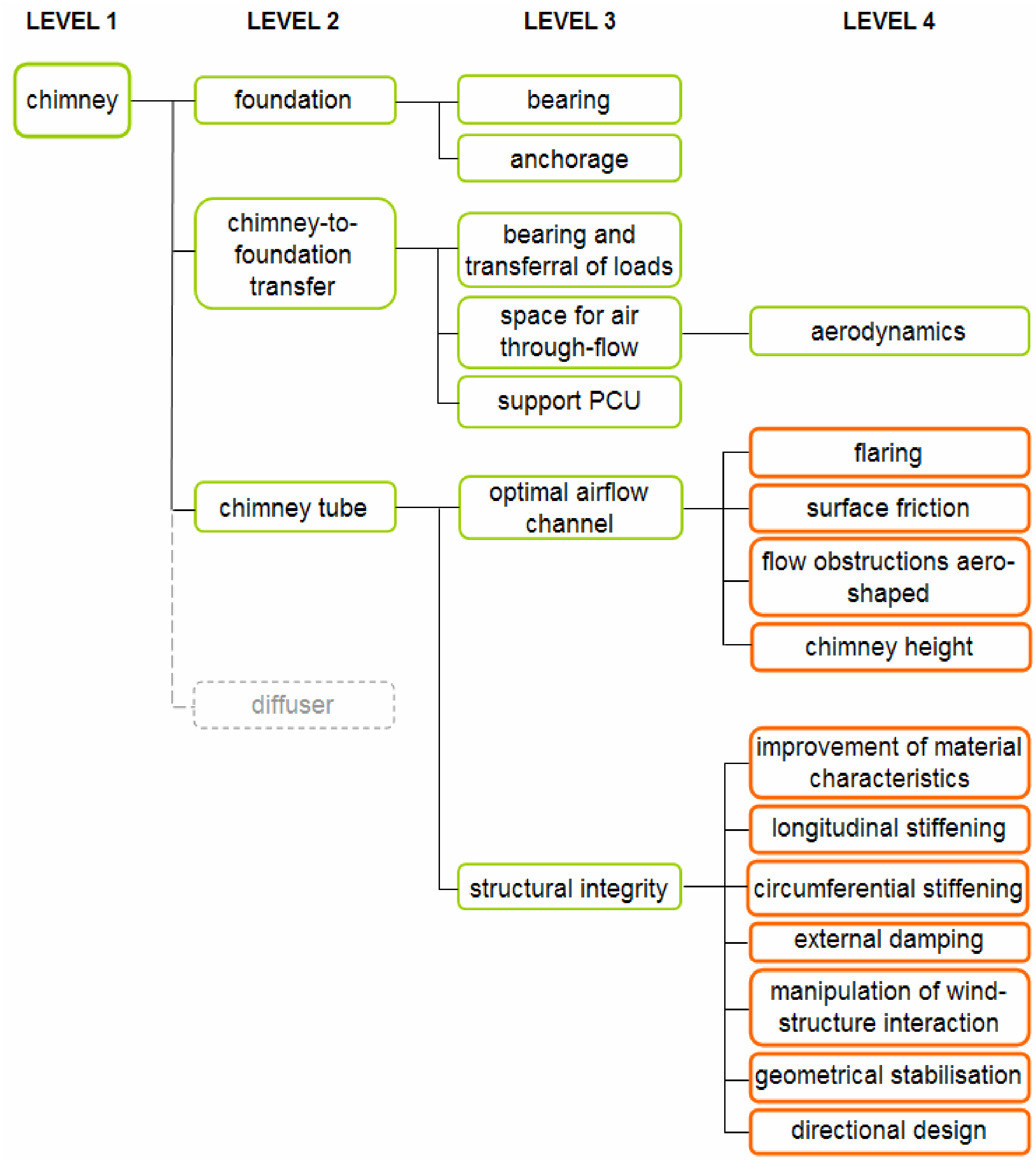

Figure 6-5. SCPP chimney system functional technology tree.

The functional flow from R&D theme through functionality to core technology as mentioned in section 2.4.3 is evident. For example, the Level 2 chimney tube system (R&D theme) breaks down into a Level 3 contradiction between the optimal air-flow channel and realisation of structural integrity. Trade-off between contradictions can be visualised and understood from a systems perspective.

The rest of this dissertation focuses on the innovation of the *chimney tube* – the technologies depicted in orange in Figure 6-5. Several of these technologies may also have an impact on the integration and configuration of foundation and chimney-to-foundation transfer subsystems (e.g. geometrical stabilisation and longitudinal stiffening technologies).

Material level failure modes (summarised in Table 6-1) are combined under one technology field, namely “improvement of material characteristics”. Materials science is a complex field with many factors contributing to its characteristics. The in-depth investigation of each material failure mode (stated in Table 6-1) is not performed here; rather, the “improvement of material characteristics” is investigated from the perspective of three material attributes that are representative of and readily used in structural design, namely the elastic modulus, weight and damping ratio. The failure modes of Table 6-1 are all influenced to a greater or lesser degree by these attributes.

In terms of the definition of radical innovation provided through Figure 2-2, the synthesis of technologies in a feasible SCPP chimney system is at this stage subject to significant uncertainties in its theoretical basis and failure mitigating technology subsystems or components. They do not attain to the sought levels of performance – development up to these levels is uncertain. Other technologies may prove to better address the functionality. These uncertainties in lower system levels perpetuate to the higher levels and become unmanageable. For example, uncertainty of realising sought material characteristics performance levels – a Level 4 functionality – perpetuates to higher system levels and becomes unmanageable in the synthesised system.

## 6.5 List of identified technologies

Technologies and theoretical uncertainties identified from information gathered up till now are listed for subsequent investigation and introduction in the RIM system evaluation phase.

The technologies identified and represented in the technology tree together with the theoretical uncertainties (discussed in section 5.3.1) are compiled to form a list of technological priorities to enter the evaluation phase of the RIM. The list is provided in Table 6-3 and is numbered; the same numbers are used in the next chapter to assist readability. Note that two technologies are added (under "General" in Table 6-3): the increase of the chimney height could decrease the LEC by increasing energy generation and the sensitivity of the wind model to terrain surface roughness could indicate sensitivity of the structure to this wind model parameter. The characterisation of trans-critical flow is sorted with the wind-structure interaction manipulation technology. The flow regime predicts specific adverse phenomena and flow characteristics that manipulating technologies aim to mitigate.

Table 6-3. List of technologies.

| **From fundamental theory** |
|---|
| 1. Wind velocity extrapolation model |
| 2. Wind direction variations over chimney height |
| 3. Applicability of prescribed critical buckling factor to SCPP chimney |
| 4. Cross wind force spectrum |
| **From technology tree** |
| 5. Chimney flaring |
| 6. Inner surface friction |
| 7. Aerodynamic circumferential stiffener |
| 8. Improved material performance (density, elastic modulus, damping) |
| 9. Cable support adding longitudinal stiffness |
| 10. Parabolic hyperboloid geometry |
| 11. Enlarged chimney diameter |
| 12. Number of circumferential stiffeners |
| 13. Wall thickness variation |
| 14. External damping devices |
| 15. Wind-structure interaction manipulation; characterisation of trans-critical flow regime |
| 16. Directional design |
| **General** |
| 17. Heightened chimney |
| 18. Parametrical wind model sensitivity (terrain surface roughness) |

The entries in Table 6-3 form the list for evaluation in the next RIM phase, whereby system alternatives are formulated and evaluated. Note that, generally, during the next phases (data gathering toward formulation of alternatives for evaluation as well as in the technology assessment phase) deeper insight into the criticality of technologies is gained which may have remained unknown up to this stage. If at any stage a technology is proven to be inadequate in contributing significantly (to achieve radical innovation) to the improvement of system functionality and performance it may be filtered out of the list to optimise R&D resources.

## 6.6 Conclusion on Solar Chimney Power Plant technology identification

During the technology identification phase of the RIM the SCPP chimney reference case is broken down into its functional hierarchy to reveal intrinsic functional subsystems and components. This *functional* perspective provides a view on the system that in not constrained by standardised design practice and theory. Specific functionalities that are required in the chimney are identified by failure mode identification. Technology scan proposes solutions for functionality against failure. The chimney functional technology tree is formulated, portraying core technology solutions as they respond to specific R&D themes. A list of technologies is compiled from this tree and the theoretical uncertainties identified during the reference case set up. This list is considered in the next phase of the RIM, where alternatives are formulated through augmentation or of the identified technologies or introduction of required functionalities.

The technology identification phase of the RIM provides the radical innovator with a systems perspective on the SCPP chimney and views the system in terms of the technological elements it consists of. Subsequent technology acquisition and strategic technology decisions can be sorted in terms of the technology tree set up in this chapter.

# CHAPTER 7

# EVALUATION OF POTENTIAL IMPACT OF TECHNOLOGIES ON THE SOLAR CHIMNEY POWER PLANT CHIMNEY SYSTEM

The RIM system evaluation phase determines the potential of technologies to impact SCPP chimney system performance. Each entry on the list of chimney technologies identified in the previous chapter is investigated for augmentation or introduction of a fitting technology solution. The different SCPP configurations resulting from augmented or introduced technologies are evaluated and compared in this RIM phase. (Note that the detailed results are not shown in this chapter as it may distract from the main development of the RIM thesis. Appendix G, section G2 contains the calculations and the resulting impacts of each technology on the various identified criteria.)

This phase of the RIM incorporates the system performance evaluation process of incremental innovation, as set out in the systems analysis process (section 2.6.2). The radical innovation perspective presented in the RIM, however, requires the augmenting of technology performance variables up to preferred values or the introduction of new technological functionality, as opposed to reverting to standard, realistic values as is typical during incremental innovation. An evaluation model is set up in response to board specified evaluation criteria making sure that the performance attributes that are significant during the current radical development phase of the chimney system are accommodated. Reference is made to the Appendices containing more detailed information concerning the evaluation model.

Alternatives are entered into the evaluation model to determine the response of each alternative to the individual criteria specified in section 5.3. Alternatives that hold the most potential are identified, distinguishing the chimney technology portfolio into a spectrum ranging between core and less significant technologies.

## 7.1 Formulation of alternatives

This section reports on the research performed to formulate sufficient detail of each of the SCPP technologies listed in Table 6-3 (in section 6.5) for engaging the augmentation or introduction of the required functionalities. The sensitivity of the SCPP system to the technologies can subsequently be investigated. The previous chapter identified the list of technologies, some indicating specific devices or concepts, such as the parabolic hyperboloid geometry, whilst others only specify general functionality with no specific solutions that satisfies the functionality identified or proposed, e.g. the external damping devices.

Note that investigations on fundamental theory (uncertainties in scientific theory – section 5.3.1) aim to contribute more detailed information to the current reference and evaluation models in order to diminish uncertainty, i.e. it aims to describe phenomena and design limits in more detail where conservative assumptions were made previously.

Not all uncertainties or augmented or introduced technologies investigated in this study gained significant progress toward identifying solutions within the resources allocated to their R&D. These are pointed out where applicable.

### 7.1.1 Wind velocity extrapolation model

A wind extrapolation curve characteristic of frontal weather systems is currently used in the chimney reference case. Three-second wind gusting data stated in a wind map in the SABS 0160:1989 Loading Code [SABS 0160 1989] form the basis of the wind extrapolation curve. The reference case wind model set up in Appendix B use a factorial adjustment of 1.53 [ISO DIS 2007] to adjust from a three-second gust velocity of 40 m/s [SABS 0160:1989] to an hourly mean wind velocity of 26.14 m/s[i]. Investigation into more detailed South African wind literature [Milford 1987] indicates an hourly mean wind velocity of 20 m/s for the Sishen region. Thus the factor adjustment translates the three-second gust velocity to a 30% higher mean hourly velocity than is reported by Milford [1987].

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[i] These values are given for a 50 year return period. The reference wind model uses a 1,000 year return period for buckling analyses and a 2,000 year return period for dynamic frequency response – refer to Appendix B for more detail.

This discrepancy/uncertainty is noted as potentially significant to the system performance improvement. Allocation of more resources to this matter may reveal the reason for the discrepancy in wind adjustment factor, making for reliable design.

The reference wind model is adjusted to implement the hourly mean wind of 20 m/s. The peak wind data (40 m/s gust velocity) remains applicable to analyses incorporating extreme winds as basis (buckling analysis – refer to Appendix C, section C1). The 20 m/s hourly mean wind data is used to determine velocities relevant in structural response analysis (refer to Appendix C, section C2). The turbulence intensity profile remains unchanged.

### 7.1.2 Wind direction variations over chimney height

Although the current mathematical formulation of a vertical wind profile shows extreme and average wind speeds, it does not predict the directional variation. With tall structures this phenomenon can cause multi-directional pressure loads which may excite resonant oscillation of the structure in its higher natural frequencies. Rousseau [2005] showed the excitation of higher vibration modes, assuming inverse loads of the fully developed wind profile.

Wind loading or meteorological literature does not contain a formulation to describe the stochastic properties of these inversions. In investigating this phenomenon, upper boundary layer wind data was acquired from the South African Weather Bureau for the Upington (near Sishen) and De Aar (south eastern tip of the Northern Cape) weather stations. Inconsistencies in the data, however, jeopardised its credibility as a statistical source – Appendix F discusses this discredit – hence this theoretical uncertainty could not be resolved within the allocated resources and was set aside until a more credible substantiation of the directional variation characteristics is found.

### 7.1.3 Applicability of prescribed critical buckling factor to the Solar Chimney Power Plant chimney

Buckling in cooling towers is prevented through design against a critical buckling factor of 5 [VGB 2005]. The applicability of this design guideline on the SCPP chimney remains uncertain. Note that although this theoretical uncertainty does not influence the structural performance of the chimney, it provides a measure against which radicality and structural performance improvements can be measured.

No progress to resolve this issue was made by way of resources allocated during this study. Future R&D must perform geometrically and physically non-linear buckling analyses incorporating initial displacements and imperfections to model actual conditions and translate these to a critical factor applying to the simplified linear elastic buckling analysis.

### 7.1.4 Cross wind force spectrum

A formulation for vortex-separation-induced across-wind excitation is provided in Appendix C. Across wind response is a function of the cross wind force spectrum (see Figure C6 in Appendix C, section C2.2). This spectrum indicates the power density corresponding to the typical velocity spectrum and is a function of the level of turbulence in the approach flow. Further, the values vary significantly with the cross section and aspect ratio of the structure. As a result, interpolation must be used if the desired aspect ratio does not correspond to those provided, or the nearest shape must be selected to approximate the force spectrum coefficient if the desired shape is not available [Kijewski and Kareem 2001]. A cross wind force spectral distribution is not available for circular cross sections and the aspect ratio encountered in the SCPP chimney – uncertainty exists about its assumed value.

A first consideration before performing in depth R&D on this subject is the sensitivity of the response to the cross wind force spectrum values. If the wind velocities reach the critical wind velocity with sufficiently low probability the cross wind force action (necessitating consideration of the cross wind force spectrum) need not be considered. A theoretical investigation into the sensitivity of the chimney performance to this parameter can determine whether resource allocation to resolve this uncertainty could provide critical insight. A force spectrum coefficient of $2\times10^{-3}$, corresponding to a reduced velocity of 4.46 m/s, is applicable to the SCPP chimney, but is based on values for structures of square cross section (refer to Appendix C and the Australian Wind Code [Australian Standards Wind Loading Code AS1170:2 1989]). This value is changed to $1\times10^{-3}$ (half that of the reference case, resulting in a factor of 0.707 on the across wind overturning moment) as an arbitrary smaller value to determine the impact trend.

Note that the reference case does not activate resonance – for this evaluation the 1,720 meter chimney is considered because of its affinity to resonant behaviour.

A more comprehensive characterisation of the cross wind spectrum could provide a better understanding toward theoretical characterisation for conceptualisation and design of a safe, cost effective chimney.

### 7.1.5 Flaring of chimney exit geometry

Significant losses are incurred due to the kinetic energy lost as the moving air meets stagnant air just outside the chimney exit. Exit losses contribute 14.9% to overall losses [Fluri and Von Backström 2006]. Flaring the upper region of the chimney geometry decreases the air through-flow rate so that less kinetic energy is lost due to air decelerating against the more stagnant air outside the chimney.

Flaring exit geometry whereby the exit area is increased by 50% over the last 110 meters is proposed (chosen to determine the impact trend), increasing the chimney diameter by 36 meters. Diameter increase is assumed to be linear with height increase.

### 7.1.6 Chimney inner surface friction

Friction losses contribute very little to overall losses. Von Backström et al. [2003] determined friction losses to be only 1% of a total turbine loss of 8.9% [Fluri and Von Backström 2006]. A numerical simulation confirmed this negligible impact of surface friction on energy yield by calculating an increase of 0.007% in annual energy yield. This potential improvement does not promise radical impact and is not considered further. It may, however, be re-considered during optimising phases later in the system life cycle.

### 7.1.7 Circumferential stiffener concept

The relevance of investigating the impact of different circumferential stiffener concepts on the system performance, through utilising the reference case simulation model (formulated in Appendix A, section A1.2), is qualified.

#### Impact on energy yielding performance

The circumferential stiffeners in the reference case configuration are responsible for an order of magnitude larger pressure drop than the pressure drop due to wall friction. Research on the circumferential stiffener geometry determined that its cross sectional shape and angle of attack have significant impact on energy yield losses. Von Backström et al. [2003] determined that rounding the bicycle spoke wheel windward sections reduces the drag coefficient by 38.5%; tapering the section tail reduces it by an additional 48.2%.

A model for determining stiffener impact on structural performance

The placement of beams or cables at positions of circumferential bending in the shell due to wind suction forces resists excessive ovalling. The impact of the number of stiffening beams in the reference case circumferential stiffener concept is representative of the efficiency of this concept in resisting ovalling. The number of circumferential stiffener beams in the reference case is halved from 72 to only 36 beams (in the FEM simulation this is achieved by releasing the appropriate vertical rotation constraint – refer to Appendix A, section A1.2. Note that this approximation stiffens the flexural resistance of the shell and does not simulate the axial cable restraint to ovalisation directly.).

Note that although several conceptual solutions for the circumferential stiffener are proposed in literature [Schlaich et al. 2004b, Lourens 2005, Glubrecht 1973] the optimal concept remains to be confirmed. A starting point from which the impact of these conceptual variations on the various criteria can be evaluated is proposed here. Future R&D should model the stiffener concepts more accurately before technological comparison and improvement of the concepts can be investigated accurately.

### 7.1.8 Improved material performance

Material characteristics have a significant impact on structural integrity. Elastic modulus, density and material damping are to some extent representative of a material's resistance to static and dynamic instability.

Material elastic modulus

Literature states the existence of ultra-high strength reinforced concrete mixes reaching elastic modulus of 60-100 GPa [Mehta and Monteiro 2006]. In the current study an elastic modulus of 60 GPa is used to augment the reference case chimney shell (the chimney only, not the fin stiffeners) material performance.

The reference concrete material cost is assumed to be increased by three times to a value of R3,000/m$^3$ (This cost increase is chosen arbitrarily in order to provide a data point from which trends of impact on the system performance can be investigated. More resource expenditure on this subject may yield a realistic cost.). Labour and plant costs are increased by 50%.

### Concrete density

Lightweight aggregate, high-strength concrete with compressive strengths of up to 60 MPa are commercially produced with high-quality lightweight aggregates [Mehta and Monteiro 2006]. Weights of as low as 1,790 kg/m$^3$ are reported. In the current study the performance trend is studied through the implementation of a density of 2,000 kg/m$^3$ on the chimney (including fin stiffeners) reference case, reducing it from 2,400kg/m$^3$.

Note that the large scale use of lower density aggregate is strongly location dependent subject to availability at specific sites.

### Internal damping

The percentage critical material damping used in the reinforced concrete of the reference case reinforced concrete is 1.43%. This value is postulated on a statistical base based on the values of the logarithmic decrement of several (smaller) reinforced concrete chimneys similar to the SCPP chimney [Rousseau 2005]. The upper trend line of the statistical data corresponds to a critical damping ratio of 1.91%. The impact of change in this coefficient on the system performance is investigated here using the upper limit value. Conclusive characterisation of SCPP chimney damping could shed more light on the applicable value for the damping parameter. Materials with higher internal damping characteristics could alter the value as well.

Note that in further materials investigation in this study the material-based parameter changes are decoupled in a parametrical study of performance results.

### 7.1.9 Cable support adding longitudinal stiffness

Cable stays are often used in practice as a measure of structural stabilisation. Telecommunication masts with high aspect ratios (Figure 7-1) and limited rotational base support are provided with sufficient longitudinal support for its realisation by the deployment of cable stays over its elevation. Instabilities in the SCPP chimney may be alleviated by cable staying although its geometry is different from telecommunication masts due to its extraordinary dimensions, lower aspect ratios, fixed base support and reinforced concrete material.

Figure 7-1. Cable stayed transmission tower at the Olympics stadium in Berlin [Internet 3 2007].

Modeling of cables poses computational difficulty due to their geometrically non-linear behaviour. An introductory study to assess the potential of increasing the structural stiffness by means of cable stays was performed [Fraser 2006]. The catenary curve of the cable under its own weight changes when forces increase due to bending of the chimney. This cable action was approximated with linear elastic spring supports at various positions along the chimney height. The height of connections was restricted to make provision for the sagging nature of catenary cables and to effectively utilise the horizontal resistance they offer. Problems of cable own weight and large force transfer to chimney shell, requiring strengthening to prevent punching shear pullout, served as practical constraints. In a system with two springs at heights of 400 and 900 meters a first global vibration frequency of 0.255 Hz was calculated – a significant improvement from the 0.1 Hz of the particular reference case used in that study. The realisation of such horizontal spring resistance by cable stays, especially at these great heights, remains to be studied in detail.

Although the behaviour of cables is a highly non-linear process which needs specialised simulation in FEM software, this first approximation of the impact of cable staying on the chimney structural integrity indicates potential warranting further investigation. The accurate characterisation of cable-stayed chimney behaviour remains to be completed; it was not further investigated due to resource constraints.

### 7.1.10 Parabolic hyperboloid geometry

Parabolic hyperboloid geometry increases stability and reduces costs in structures by its inherent geometrically based strength. The investigation into the marriage of hyperboloid geometry with the ultra-high rise SCPP chimney could decrease the high material volume needed to adequately stiffen the chimney against buckling and cantilever pushover, currently brought about by way of the voluminous fin structures.

A hyperboloid concept (Figure 7-2) is set up for this study based on guidelines from the VGB [2005] and incorporated in the lower region of the chimney while excluding the fin structures. A base angle of $20.6^o$ to the vertical is used diminishing to $0^o$ at a height of 400 meters. The reference case wall thickness configuration is used in the hyperboloid concept, decreasing linearly from 2.15 meter at 25 meter elevation to 0.3 meter at 1,000 meter elevation, remaining constant up to the chimney tip. Although a benefit of parabolic hyperboloid geometry is the reduction of wall thickness and material volume, enough can be learnt from the initial implementation of this geometrical concept that a detailed wall thickness optimisation carries *subsequent* priority (it was not further developed for this study). Cylindrical columns of 8.87 meter diameter transfer forces in the shell structure to foundational level, creating space for air through-flow. (The columns are modeled in FEM by L12BE two node Bernoulli beam columns that are constrained against all translation and rotation at the foundational level node.) Circumferential stiffener geometry and location remain unchanged from that of the reference case. The foundational capacity is sufficient for bearing of this geometrical change based on the calculations from Appendix A1.2.

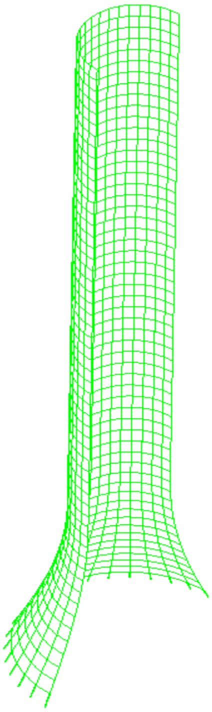

Figure 7-2. The FEM mesh for analysis of the SCPP chimney incorporating parabolic hyperboloid geometry.

### 7.1.11 Increased chimney diameter

The prospect of an increased chimney diameter promises a significant increase in energy yield by containing a larger volume of heated air (refer to section 5.2.1); it should also increase global cantilever bending resistance. In this conceptual change the chimney diameter is increased to 200 meters while all other parameters remain unchanged.

### 7.1.12 Number of circumferential stiffeners

The influence of the number of circumferential stiffener systems on the mitigation of local buckling modes and circumferential flexural stresses in the system is investigated in the current study. One stiffener is added between each current pair in the reference case, i.e. five additional stiffeners. The eleven circumferential stiffener wheels (six from the reference case and five added here) are located at heights of 1,500 meters, 1,390 meters, 1,280 meters, 1,170 meters, 1,060 meters, 950 meters, 840 meters, 730 meters, 620 meters, 510 meters and 400 meters.

### 7.1.13 Wall thickness variation

Stiffening against local buckling modes and reduced flexural stresses can be achieved by re-configuration of the wall thickness. The proposed wall thickness configuration is based on contemporary cooling tower designs – see Figure 7-3a – where wall thickness rapidly decreases from a relatively thick base to a thin shell and remains approximately constant to the top [Harte et al. 2007]. The proposed configuration in Figure 7-3b is based on a pre-feasibility project proposal by Harte and Krätzig [2007]. In this configuration the wall thickness is generally thicker than the design in Figure 7-3a but tapers down to a value of around 0.40 meters in the upper parts of the chimney. It is assumed that the inner diameter remains constant over height.

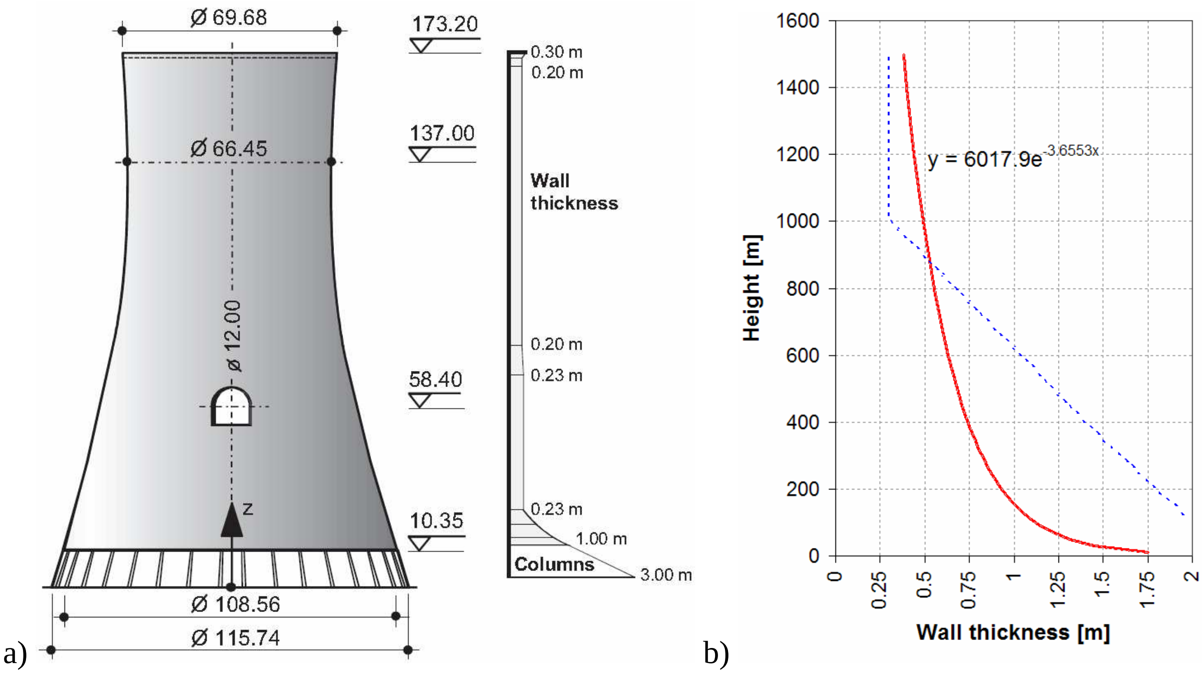

Figure 7-3. a) Dimensions and wall thickness of a 173.2 meter tall cooling tower [Harte et al. 2007]. b) The reference case (blue dashed line) and the investigated wall thickness (red solid line) configurations.

### 7.1.14 External damping devices

Resonant structural response in structures due to dynamic effects can be damped utilising external damping devices and vibration controls such as tuned mass dampers and sloshing liquid dampers. Several of these control devices were implemented in practice successfully reducing undesirable vibration levels [Datta 2003].

This performance evaluation does not further engage the complex technical field of external damping due to resource constraints but qualitatively identifies it as a possible measure in mitigating resonant response in the SCPP.

### 7.1.15 Wind-structure interaction manipulation

The surface roughness of a structure has a significant influence on the flow characteristics around its cross section; the smoother the surface the higher suction (negative pressure) [VGB 2005]. Wind tunnel experiments on the SCPP chimney confirmed this coefficient to decrease to as low as -3.0 [Harte and Van Zijl 2007]. The manipulation or mitigation of these high suction forces could have significant implications for realising SCPP chimney structural integrity.

Saguaro cacti are natural, tall cylinders that generally have high slenderness ratios of up to 18.75 (see Figure 7-4a); still, they endure wind flows with Reynolds numbers (Re) of up to $1.10^6$ placing it in the trans-critical flow regime alongside the SCPP chimney. The root to soil interface determines the load bearing capacity of a Saguaro because toppled Saguaros usually are found uprooted rather than broken at the trunk; its ability to mitigate wind loading is believed to lie in its ribbed surface geometry [Alberti 2006, Talley and Mungal 2002] – see Figure 7-4b. Note that these ribs are not to be confused with cooling tower ribs.

The Saguaro geometry was simulated experimentally and numerically as a multiple rib configuration to study its effect on wind-structure interaction [Alberti 2006]. The research yielded important results for the SCPP chimney, as reported in Van Dyk et al. [2006]; note that the Saguaro geometry has potential mitigative application on a range of failure modes:

The drag coefficient[ii] ($C_D$) of smooth surfaced cylindrical shapes is generally lower (approximately 0.55) than those of the ribbed shapes (approximately 0.8) at the high Re

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[ii] The drag coefficient is a dimensionless quantity that describes a characteristic amount of aerodynamic drag caused by fluid flow. Cross sectional shape has a significant effect on the drag coefficient.

present in SCPP chimneys. This observation is applied to determine the overturning moment during dynamic response calculations (refer to Appendix C, equation C2).

Figure 7-4. a) A forest of Saguaro cacti [Internet 2 2008]. b) a cactus depicting cavities on the circumference [Talley and Mungal 2002].

The smooth surfaces display a sudden decrease in $C_D$ from 0.85 to 0.40 at the “critical” Re. The decrease in drag coefficient could augment along-wind velocity fluctuations causing along-wind dynamic response. Recent experimental results show that ribbed surfaces portray no decrease in $C_D$ over a wide Re range, including the critical range for smooth cylinders of the same global geometry, showing that the Saguaro geometry circumvents this augmentation.

The roughness of the surface area shifts the sudden decrease in $C_D$ toward the left, i.e. at increased surface roughness the sudden decrease occurs at lower Re. This decreases the critical Re, moving further away from the generally high SCPP chimney Re.

Slight imperfections along the surface area, as are always evident in actual constructions, cause localised peaks in pressure coefficients from -2.0 to -2.5 on the outside wall of the chimney as is portrayed in Figure 7-5a. These high coefficient peaks are almost completely mitigated [Alberti 2006] by the introduction of ribbed surfaces with new coefficients of larger than -0.8 (see Figure 7-5b).

Furthermore, it is postulated that the absence of uneven vortex shedding (refer to the third point under section 5.3.1 and to section 7.1.4) in the trans-critical flow regime eliminates the threat of cross-wind oscillation [Alberti 2006]. This is due to the presence of a turbulent boundary layer around the circumference of the SCPP chimney at the encountered Re numbers. The confirmation of this postulation would imply the non-occurrence of alternate vortex shedding and, hence, no across wind resonant excitation.

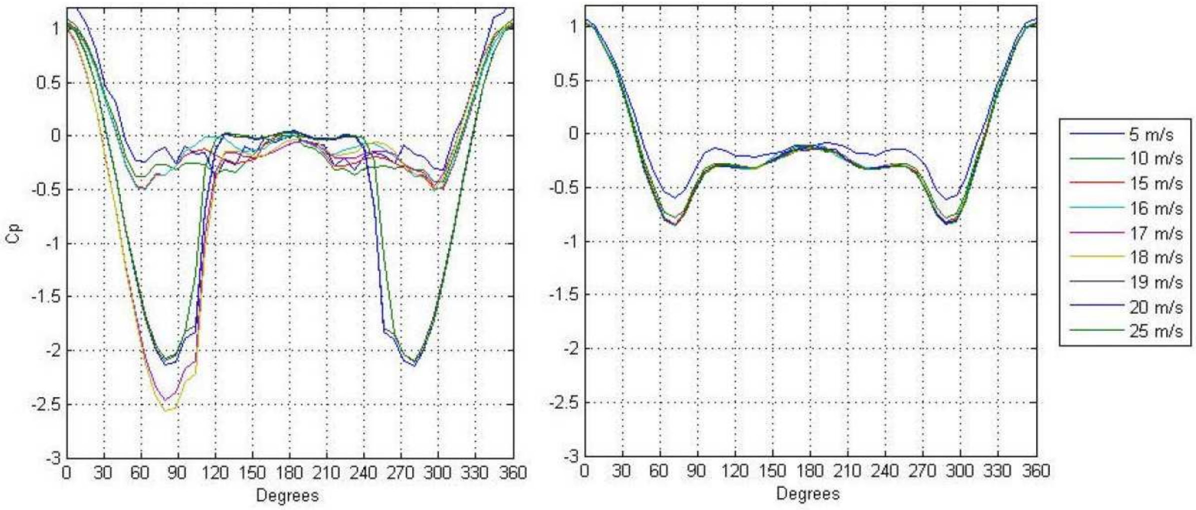

Figure 7-5. External pressure coefficients at various wind velocities for a) smooth cylinders and b) ribbed cylinders [Alberti 2006].

The circumferential pressure coefficient distribution used to investigate the impact of Saguaro geometry, based on Figure 7-5b, is depicted in Figure 7-6 – the orange line. (Note that the net pressure coefficients are portrayed – external pressure *and* internal suction pressure; hence the orange line value of 1.8 (unity pressure plus internal suction) at zero degrees.) The internal suction coefficient under no internal flow of -0.8 applies (refer to Appendix B, Figure B-3). Note that the reference case used the load case where internal flow occurs due to its large suction coefficients (Appendix B, Figure B-2). The “no internal flow” data is the only Saguaro geometry measurements made. These are subsequently applied in the Saguaro geometry alternative. Future research must determine the circumferential pressure coefficients for the Saguaro geometry *with* internal flow.

The Saguaro based geometries investigated by Alberti [2006] consisted of 45 and 90 spikes each protruding radially up to a length of 14% of the cylinder radius. The simulation of Saguaro geometry in this dissertation considers the lower limit case where the cactus geometry plays no structural role. The non-structural Saguaro geometry serves as a lower limit from a cost and structural integrity perspective. This is incorporated into the extreme wind load applied during buckling analysis (refer to Appendix C, section C1) by means of a multiplication factor of 1.14 based on the enlarged chimney frontal area (14% radius increase = 14% area diameter increase). The width parameters in the dynamic response calculations (refer to Appendix C, section C2) are set to 160 meters × 1.14 = 182.4 meters. Note: this area factor is not applied to the fin stiffeners as they already present a type of wind manipulating geometry.

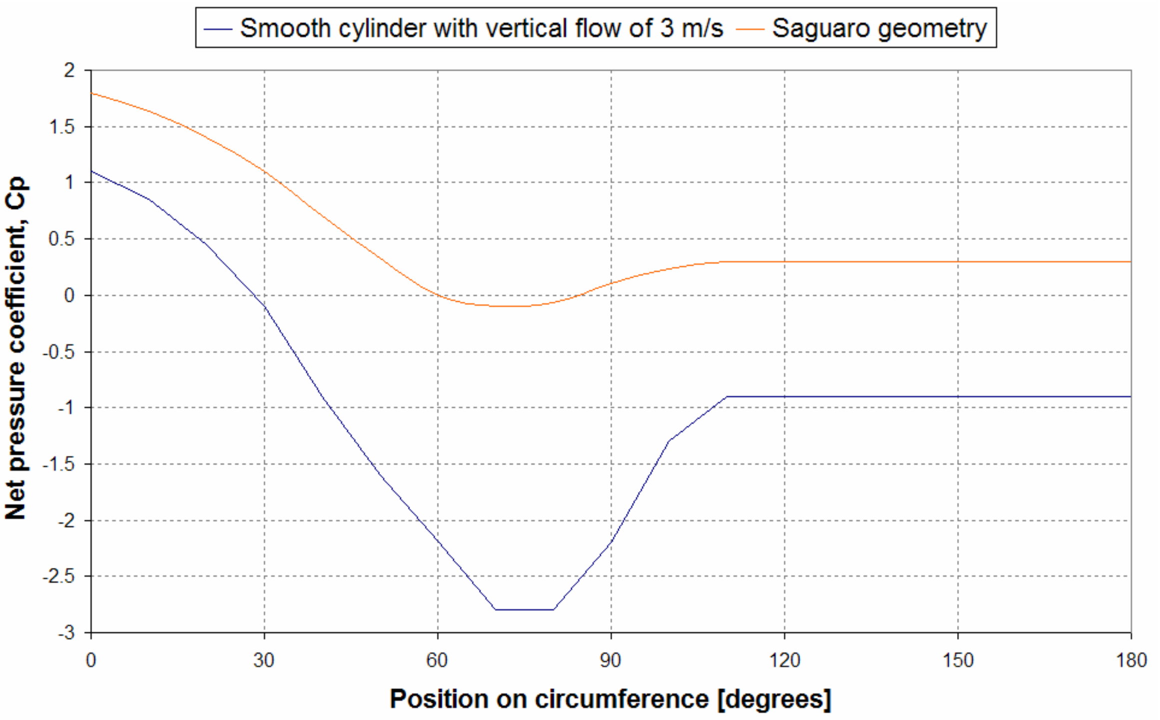

Figure 7-6. Net circumferential pressure distribution without and with incorporation of Saguaro geometry.

### 7.1.16 Directional design

Wind generally prevails in specific directions. Figure 6-4 in section 6.3.6 displays a visualisation of wind prevalence, wind speed and wind calms (when no or nearly no wind blows). Statistical processing of this data over several years provides an indication of the long-term wind prevalence.

Design winds are typically based on the extreme wind condition over *all* directions and structures are accordingly designed rotationally symmetric [Niemann 2007]. In nature, however, trees react only to extreme wind in specific directions: trees tilted by the wind, even if only slightly moved from a vertical orientation, produce modified cells along the bole called “reaction wood” [Chaney 2001], in the future better resisting winds in these directions. This phenomenon suggests that the chimney structure can be designed and constructed asymmetrically in response to directional variation in loading thus decreasing costs. Figure 7-7 illustrates this concept with the left most cross section requiring adequate resistance (tension reinforcement and compressive concrete section) against the extreme wind (red arrow) while the cross section in the center depicts the same structure but under a smaller load from the opposite direction (blue arrow) requiring less tension reinforcement and a smaller compressive concrete section. The two sum to provide the cross section on the right of the figure, portraying circumferentially varying cross sectional reinforcement and wall thickness, saving on material volume in the cross section.

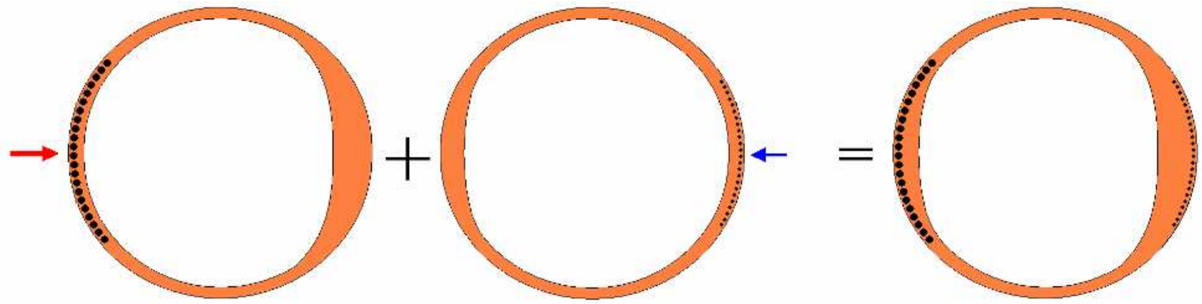

Figure 7-7. An example of directional design.

An investigation must be performed to determine the wind statistics for directionality up to 1,500 meters and the feasibility of this design approach to decrease material volume (hence, capital cost) while not compromising structural performance. This aspect was not further investigated due to resource constraints.

### 7.1.17 Increased chimney height

The increase of chimney height predicts increased energy yield (refer to section 5.2.1 for SCPP operating principles). The chimney height is increased with 220 meters up to 1,720 meters in order to determine corresponding system performance trends.

The calculations for determining the appropriate change in wall thickness is not performed since it carries secondary priority to the approval of conceptual increased chimney height (refer to section 7.2.10). The current investigation assumes a constant shell thickness in the added chimney shell of 0.3 meters with the wall thicknesses in lower regions remaining unchanged. One additional circumferential stiffener is deployed at the 1,720 meter elevation, i.e. at the chimney tip.

### 7.1.18 Terrain surface roughness

The terrain surface roughness characteristic is investigated here in order to portray the impact of optimal site choice on the structural performance. A surface roughness coefficient[iii] of $z_0 = 0.01$ is chosen (refer to Appendix B to see where $z_0$ applies to the wind model – the reference case uses $z_0 = 0.02$). The realisation of this surface roughness coefficient may entail not only the choice of optimal surfaced construction site, but also the manipulation of upstream[iv] surface characteristics (bear in mind the presence of a large, flat, smooth surfaced collector upstream from the chimney). Furthermore, directional wind statistics may indicate extreme loading limited to one radial region in which case a site downstream in this radial direction with a low surface roughness region could be identified. Figure 7-8 indicates the decrease of the reference peak wind velocity profile due to the less rough terrain (the reference case uses $z_0$=0.02).

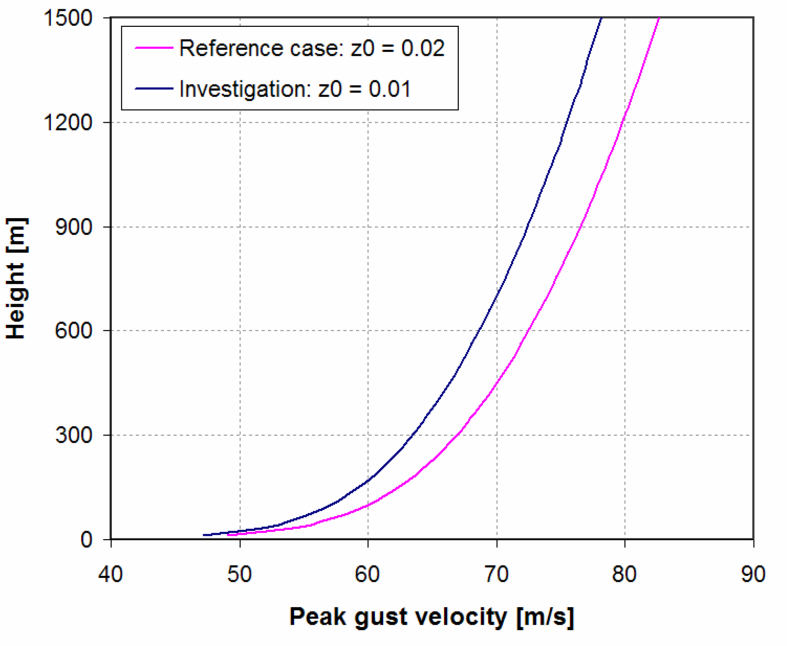

Figure 7-8. Decrease in wind velocity profile due to lower surface roughness.

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[iii] The surface roughness length defines the height at which the wind profile extrapolates to a zero wind speed gradient; it is a function of the height of roughness elements of the surface [Tyson and Preston-Whyte 2000].

[iv] Wind profiles require constant upstream terrain characteristics as far as one kilometer (and even 5 kilometers for cities) to fully develop [JCSS 2001].

The alternatives are now (semi-) quantified and ready for the next RIM step, i.e. evaluation. Evaluation criteria are stipulated in the next section in accordance with requirements set forward by the board.

## 7.2 Evaluation model and choice of criteria

The appropriate choice of criteria as evaluation metric in the RIM is critical to set up an evaluation model that is representative of the critical, governing elements of the (first iteration reference case) concept. Radical innovation is often measured with the same criteria and expectations used to assess incremental innovation, leading to a warped basis for decision-making (refer to section 2.5.2). Where the evaluation model of incremental innovation evaluates performance in terms of standard limit state equations, radical innovation requires a more accommodating model in case technologies from differing fields, with differing governing parameters and equations, are presented. Decisions during radical innovation should be based on the envisaged benefits of the preferred state of performance of the technology and the potential resulting market size.

This section provides background on the choice of criteria. It subsequently re-articulates user requirements and interprets them in terms of criteria applicable to the SCPP chimney.

### 7.2.1 Background on choice of criteria

RIM principles could apply to all levels of the system development phase, taking into account that with each lower level, more detail and more certainty is required (section 1.6.1). Similarly the set of criteria on which a system is evaluated incorporate more detail with increasing system depth. In the case of the SCPP chimney radical innovation the conceptualisation phase demands insight into the surroundings of the concept in order to understand and improve it. This may entail comprehensive investigation into technology development but only in terms of satisfying the criteria as defined in the radical innovation life cycle phase (Table 2-1 in section 2.5.2), i.e. in terms of benefits of the technology to a potential market.

Table 2-1 in section 2.5.2 is reinterpreted for the SCPP chimney. The impact of life cycle phase on the evaluation model follows in Table 7-1, distinguishing between conceptual, pre-feasibility and feasibility considerations. Note that the evaluation model and criteria must remain flexible to accommodate changes in the conceptual formulation with potentially different behavioural phenomena and failure modes.

For computational simplicity the evaluation model should only involve significant and discriminating criteria.

Table 7-1. Change of evaluation model with life cycle phase.

| **Life cycle phase** | **Variability in chimney formulation – presented by adequate criteria choice** |
|---|---|
| Radical, conceptual | Significant changes in chimney concept, geometry, or configuration could lead to significant changes in evaluation model and relevant criteria. |
| Pre-feasibility | Changes in chimney concept are minimised but may occur in concurrence with a specific site in mind. Optimisation is parametrical rather than conceptual. |
| Feasibility | Change occurs only in the detail; in project specific interaction with local environment (economical, political, ecological, social and technological) and in detail design specifications (reinforcement, fastenings, surveying, etc.). |

### 7.2.2 Re-articulation of user requirements in the choice of evaluation criteria for Solar Chimney Power Plant chimney

The reference case was set up in response to the requirements of a clean, non oil-using, cost-effective energy generation solution, as stated in section 5.1.3. These requirements also govern the evaluation criteria at the radical innovation phase. Relevant, representative criteria are identified and expounded below:

<u>Electricity cost</u>

The SCPP chimney must be evaluated in terms of cost to fulfill its primary criteria – the generation of clean, non-oil-using, cost-effective electricity (section 5.1.3). This is done through the levelised electricity cost metric as was introduced in section 5.3.2.

Annual energy yield and system costs are hereby combined for each alternative and can readily be compared to conventional electricity costs.

Structural integrity

The secondary SCPP chimney evaluation criteria – that of containment of the primary cost-effective electricity generating functionality, in accordance with the criteria breakdown in section 2.5.2 – is represented by the structural integrity required to uphold the air through-flow channel.

Unlike the mature level of theoretical characterisation of the SCPP energy generating performance, the insight into the SCPP chimney structural integrity is not yet as mature. Radical innovation is still necessary and the chimney is evaluated in a broadly conceptual sense where structural integrity and cost reduction require major conceptual and configurational changes or realisation of technology.

Codified limit state design in Structural Engineering requires quantification of structural resistance to design actions. Resistance and loading factors are deployed to accommodate reliable design. Compliance to limits is sought in all – and often very localised – parts of the system. These localised stresses could be resisted through adequate geometrical design (in the case of thin shell reinforced concrete, added wall thickness and reinforcement detailing) and are not necessarily indicative of the source of failure of the innovation concept which must be addressed through technology acquisition. Governing structural behaviour is sought and must be indicative of the response to root-cause of failure modes.

In the SCPP chimney global buckling and dynamic wind excitation sufficiently circumscribe these modes (these structural integrity criteria were already hinted in the reference case set up in section 5.2 and in the estimation of radicality in section 5.3). *Global buckling* represents global instability under compressive loading conditions. *Dynamic wind excitation* presents structural response that is typically larger than the static case; a quasi-static factor combined with simple static analysis provides for dynamic structural response, in this case when the SCPP is subjected to dynamic extreme along and across wind loading. The theoretical formulation of these criteria is presented in Appendix C.

Note that although codified reliability based parameters are included in the reference case design (e.g. the 1,000 and 2,000 year wind return period factor – refer to Appendix B), reliability based design methods, that incorporate the material stress and load statistics mentioned earlier in this section, are at this stage not implemented as structural performance measures. Reliability based design methods entail the set up of limit state equations *for each failure mode for each conceptual variation*, as well as the gathering of statistical information of limit state variables. This procedure is resource intensive and is, hence, not considered at this stage of SCPP chimney innovation where the investigation of several concepts is commonplace. Theoretical uncertainty (section 5.3.1) can also be described through reliability measures (reliability increases with an increase in theoretical insight). As soon as a chimney concept is fixed reliability methods should be applied to gain insight on further technological acquisition required to realise a reliable chimney design.

### Constructability

At this radical innovation stage of the chimney development its constructability – whether it is possible to realise the structure in terms of construction capability and logistical feasibility – could be the factor governing project success. Examples of constructability challenges concern the elevation at which upper elevation phases of the construction takes place, e.g. a construction capability to pump concrete to 1,000+ meter heights is required while the climate at 1,500 meter elevation may have adverse implications on concrete strength performance and logistical support of construction.

Due to constraints in resources this presumably critical criterion is not further investigated in this study. Further reference to this aspect can be found in a study by Lorek [2007]; the feasibility of constructing the SCPP from the perspectives of construction techniques and availability of building materials was looked into. Future research on the SCPP must further consider this critical aspect.

### Multi-criteria approach

Multi-criteria decision-making (MCDM) methods where briefly mentioned in Section 2.5.3 as a way of gaining critical overall perspective on complex system performance in terms of various criteria. Its application on the current radical innovation of the SCPP chimney is, however, complex due to correlations between criteria – orthogonality between criteria is required. As an example, consider standard design circumstances where a structural improvement is represented by associated cost decrease. With the current stage of SCPP chimney development significant uncertainties over its structural integrity govern decision-making and a mere representation in cost criterion is not conclusive for focused decision-making. The allocation of MCDM weighting factors to each criterion as a measure of its criticality to overall system performance would at this stage be arbitrary; hence, criteria are (treated as being) decoupled in this dissertation.

## 7.3 System performance evaluation

With the required analyses performed and data gathered for all alternatives, their impacts on the system performance are now determined, relative to the specified criteria. The structural evaluation model is presented in Appendix C. The cost model is presented in Appendix D. Information on the SCPP energy yield model is presented in Appendix E. Technological augmenting and introduction are incorporated in the reference case models to investigate technological performance, thus forming the various alternatives. Some alternatives could not be incorporated in the simulations. These cases are stated explicitly.

Individual results of the impact of the alternatives on the evaluation models are presented in Appendix G, section G2. Aggregated results are reported in Appendix G, section G3, in Tables G-25 and G-26. The impacts are related to their positioning between the reference case and the ideal result values stated in section 5.3.1. A zero value represents 0% improvement and a 1.00 value represents the realisation of the ideal result (100% improvement), with linear variation in between. Values are normalised and presented in order for a positive outcome to imply a positive implication for system performance. Visual representation charts, facilitating discussion of the LEC, buckling and dynamic response criteria, follow in this section. A comparative perspective between criteria provides perspective on their criticality to the SCPP technology endeavour. This in turn is followed by a vector based visualisation approach providing insight into technological performance growth.

This discussion of the technology performance results is an integral stage during any innovation for identifying developmental potential, gaps and shortcomings. Some technologies excel and should receive more resources for potential development up to the augmented or introduced performance. Other technological functionalities are not fully developed; resources could be allocated to develop these functionalities up to maturity before more conclusive judgement of its contribution to system performance can be made. Other technologies fall short of sufficient performance levels and acquisition of functionality must focus on its resolution. Each chart is now discussed.

Note that the lower and upper limits and quantitative estimations are not represented in the graphs in this section. Thus, some technologies appear not to impact performance at all. The graph must therefore be judged in consultation with Table G-25.

### 7.3.1 Levelised Electricity Cost performance chart

The LEC performance chart (Figure 7-9, based on data from Table G-26 in Appendix G, section G3) reveals the parabolic hyperboloid geometry to significantly reduce costs from R8.648/kWh to R3.756/kWh; this covers 64% of the needed improvement to reach LEC ideality[v]. The increase in chimney height provides significant increased energy yield at relatively low cost increase to cover 15% of the ideal decrease in LEC. Other notable cost reductions are the wall thickness re-configuration (5%) and the flaring chimney exit (3%).

High material costs cause development on material elastic modulus to score poorly, implying an adverse impact on the chimney cost. Material density reduction and inherent damping (currently at 0% representing lower limit costs) could further increase costs.

Note that some theoretical uncertainties (wind velocity extrapolation model and terrain surface roughness) do not perform on this chart at all and was consequently not represented; although they may indirectly reduce structural costs, for example by improved characterisation of conservative loading assumptions, their LEC performance is not measurable at this early stage of the radical innovation.

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[v] One would think that such a large cost reduction should have been incorporated in the reference case. Note, however, that the reference case was set up with the *best knowledge available*; by implication this cost reducing technology was not yet enjoying sufficient priority to justify its incorporation in the reference case. This illustrates how the systems approach facilitates the comprehensive identification of opportunities for development during the radical innovation.

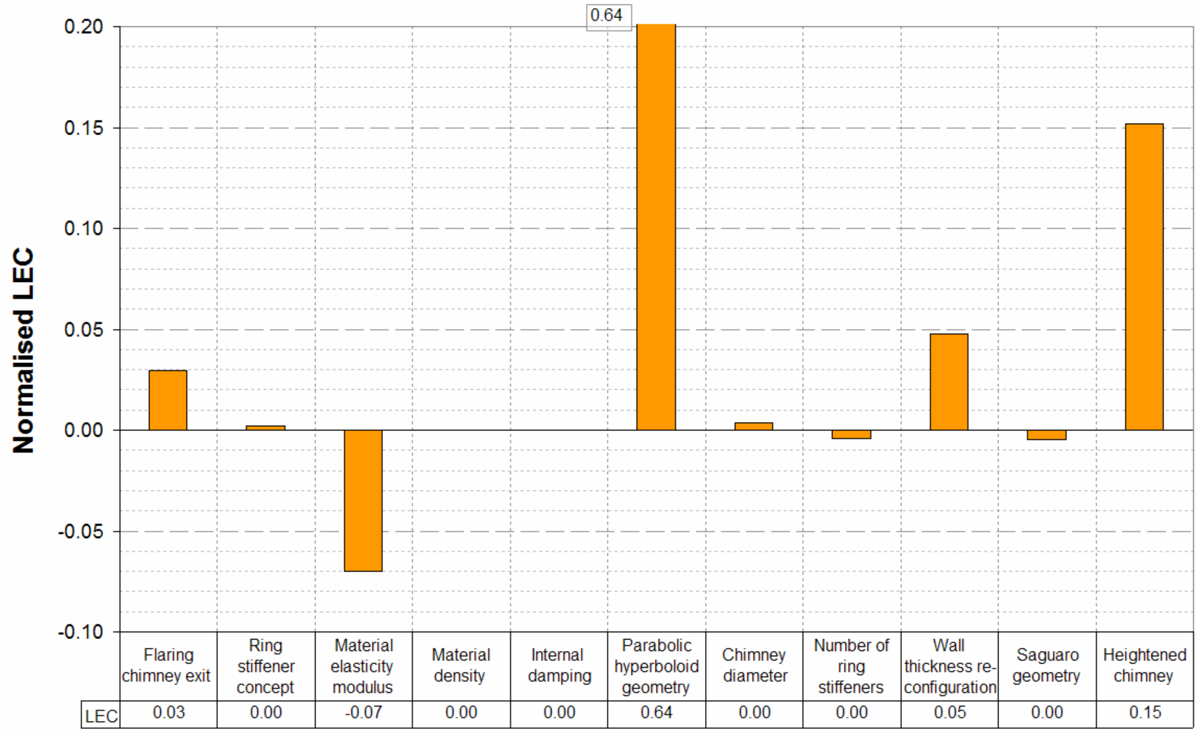

Figure 7-9. Normalised LEC performance for various alternatives.

### 7.3.2 Buckling performance chart

The buckling performance chart (Figure 7-10, based on data from Table G-26 in Appendix G, section G3) reveals several technologies that score well in this metric. Wall thickness re-configuration performs the best at 63% of the ideal improvement, the material elastic modulus increase doubles the reference case critical buckling factor to 48% of the required improvement, the added circumferential stiffeners contribute 32% improvement and the wind velocity extrapolation model 31%. Terrain surface roughness and the Saguaro geometry contributes a potential 12% and 9% (lower limit), respectively. Note: these technologies in combination could mitigate buckling completely.

The flaring chimney geometry, increased chimney diameter and different circumferential stiffener concept have adverse impact on performance by -28%, -15% and -13%, respectively. Note that the material density, internal damping and parabolic hyperboloid geometry do not contribute to the buckling performance.

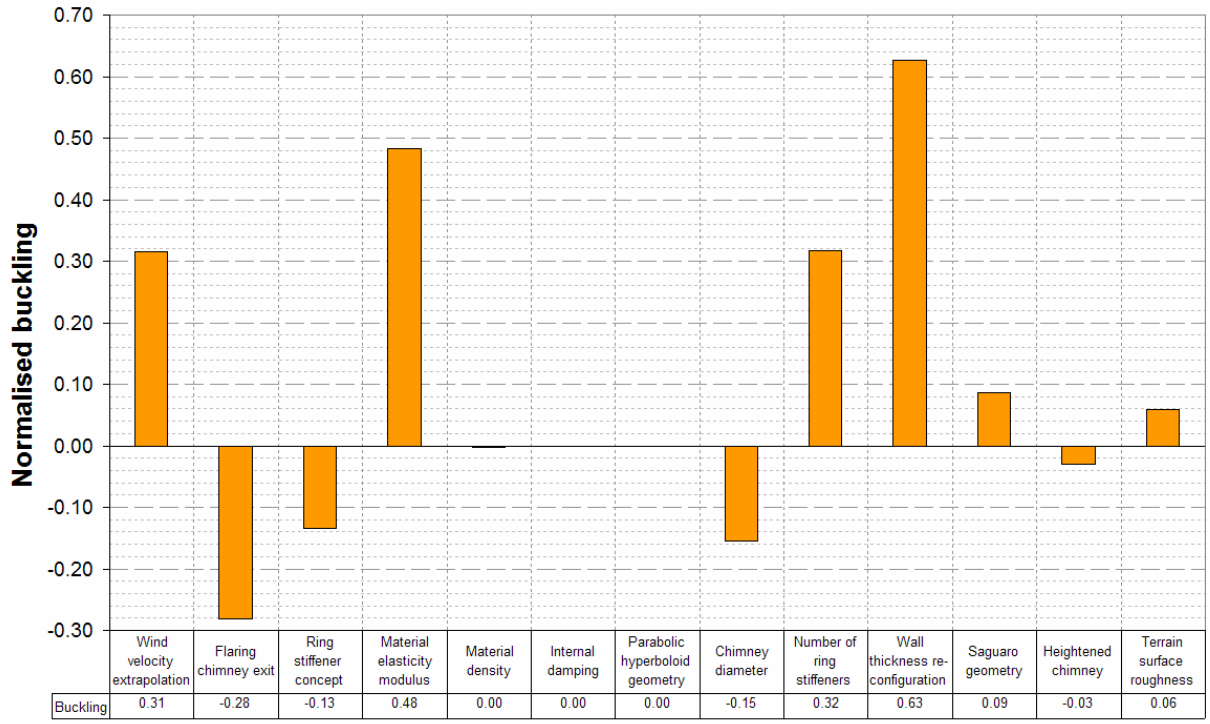

Figure 7-10. Normalised buckling performance for various alternatives.

### 7.3.3 Dynamic response performance chart

The dynamic response performance chart (Figure 7-11, based on data from Table G-26 in Appendix G, section G3) reveals several technologies that improve the dynamic response *far exceeding* the ideal requirement. Material elastic modulus contributes more than four and a half times the required 100% for ideality, terrain surface roughness contributes more than three times, increased chimney diameter and wind velocity extrapolation contributes just below four times, internal damping contributes more than double and material density one and a half times.

This criterion is also functional in portraying adverse impact on dynamic structural response. Two technologies would, if they are implemented in their current formulation, expose the system to critical adverse dynamic response, i.e. wall thickness configuration and increase in chimney height. These both score poorly due to their proximity to critical wind velocities with consequent lock-in behaviour. Note that the implementation of the cross wind force spectrum mitigates the adverse dynamic response in the increased chimney height alternative by almost three times. The parabolic hyperboloid technology also portrays adverse impact.

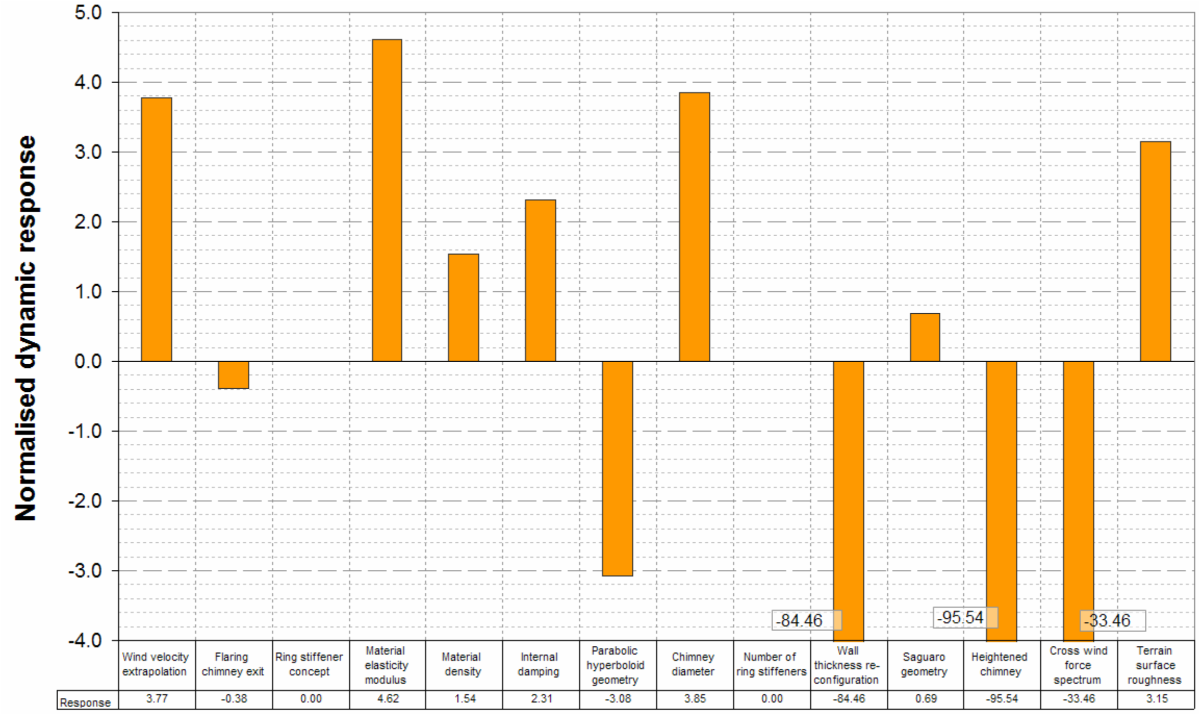

Figure 7-11. Normalised dynamic response performance for various alternatives.

### 7.3.4 Relative performance and contradictions

A systems perspective on technological impact – its performance in several governing criteria – provides a framework from which technological trade-off can be managed toward realising an optimal SCPP chimney system. With the specific gaps and contradictions identified, technologies can be acquired to fulfill the required functionalities. For example, external damping or cable staying mechanisms can be implemented against adverse dynamic response in wall thickness configuration (negative impact of this technology) in order to utilise the positive elements in the impact of this technology. Note that a thoroughly implemented MCDM approach would compact the charts (in sections 7.3.1-3) that is set up for the decoupled criteria into one comprehensive chart which may serve communicating RIM findings better.

The criteria are compared by visual means in Figure 7-12. Note that dynamic response is not included for better visualisation of the other two criteria, because its impacts are significantly larger (in terms of percentage) than the other two criteria. From the figure it is clear that LEC contribute less improvement (in terms of the respective technologies) than buckling – four technologies score well in the buckling criterion while only one scores well in the LEC criterion. R&D allocation toward mitigating buckling may contribute more successful technologies than to further LEC reduction. Note, however, that the significant LEC reduction of parabolic hyperboloid contributes significantly to the SCPP system feasibility as a cost-effective energy generation technology.

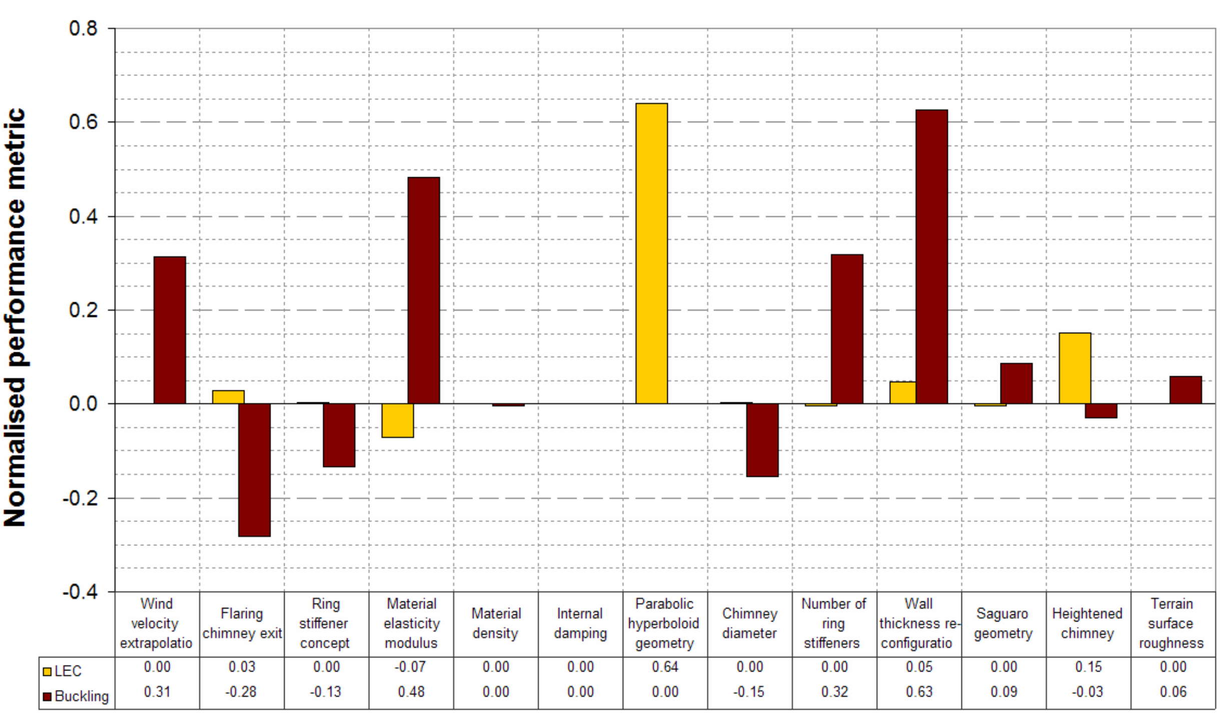

Figure 7-12. Combination of the LEC and buckling charts to provide a perspective on overall performance.

Another aspect deduced from Figure 7-12 is the contradictions (or correlations) in the impact of individual technologies on the various criteria, e.g. the wind velocity extrapolation decreases the wind action resulting in positive impact on both buckling and response criteria (refer to Figure 7-11 for response results). The adverse response to the buckling criterion of the flaring geometry could be off-set by a slight LEC increase. The circumferential stiffener concept has little impact on cost but significant impact on buckling behaviour. Material elastic modulus scores well in the buckling and dynamic response criterion, but results in an increase in LEC. Material density and internal damping mitigates adverse dynamic response, but does not score in the other criteria. The parabolic hyperboloid scores well in LEC reduction with (relative) adverse response to the dynamic response criterion. The increased chimney diameter mitigates dynamic response, but with adverse impact on buckling. The number of circumferential stiffeners increases buckling mitigation with little effect on other criteria. The wall thickness re-configuration scores well in buckling mitigation but fails in dynamic response. The Saguaro geometry has positive (lower limit) impact on buckling and response, with small (lower limit) impact on LEC.  The increased chimney height scores well in LEC reduction but fails in dynamic response. Terrain surface roughness decreases the wind load with consequent positive impact on buckling and dynamic response.

### 7.3.5 Technology growth

Technology performance trends are not evident in the previous charts. Representation in Figures 7-13, 7-14 and 7-15 provides a vector approach (developed in this study) where the measure of improvement on performance as well as the *rate of improvement* relative to other improvements – and ideal improvement – are portrayed, thus providing more information on technological potential. These graphs portray linear technology performance change, based on the position of one performance data point relative to the reference data point (0;0). Further data points could provide important information about the linearity/non-linearity of technological performance trends. Note that the upper right quadrant represents the "favourable" region for technological performance.

Buckling portrayed against LEC performance in Figure 7-13 yields the following interesting insights. Parabolic hyperboloid geometry and chimney height increase, as well as wall thickness re-configuration and material elastic modulus, yield growth toward the favourable quadrant. No technologies do, however, contribute diagonally in the direction of the ideal result. They contribute either in the one or in the other criteria and therefore remain on the periphery of the favourable quadrant.

Dynamic response portrayed against LEC performance in Figure 7-14 also yields a few technologies on the perimeter of the favourable quadrant (material elastic modulus, terrain surface roughness, increased chimney diameter and wind velocity extrapolation), but with no impact on LEC performance. Material elastic modulus and the parabolic hyperboloid geometry diverge from the favourable quadrant. The wall thickness re-configuration and increased chimney height, drive technology performance in the opposite direction of positive impact (in terms of response), with the implementation of the smaller cross wind force spectral value decreasing the adverse dynamic response in the increased chimney height alternative by almost three times.

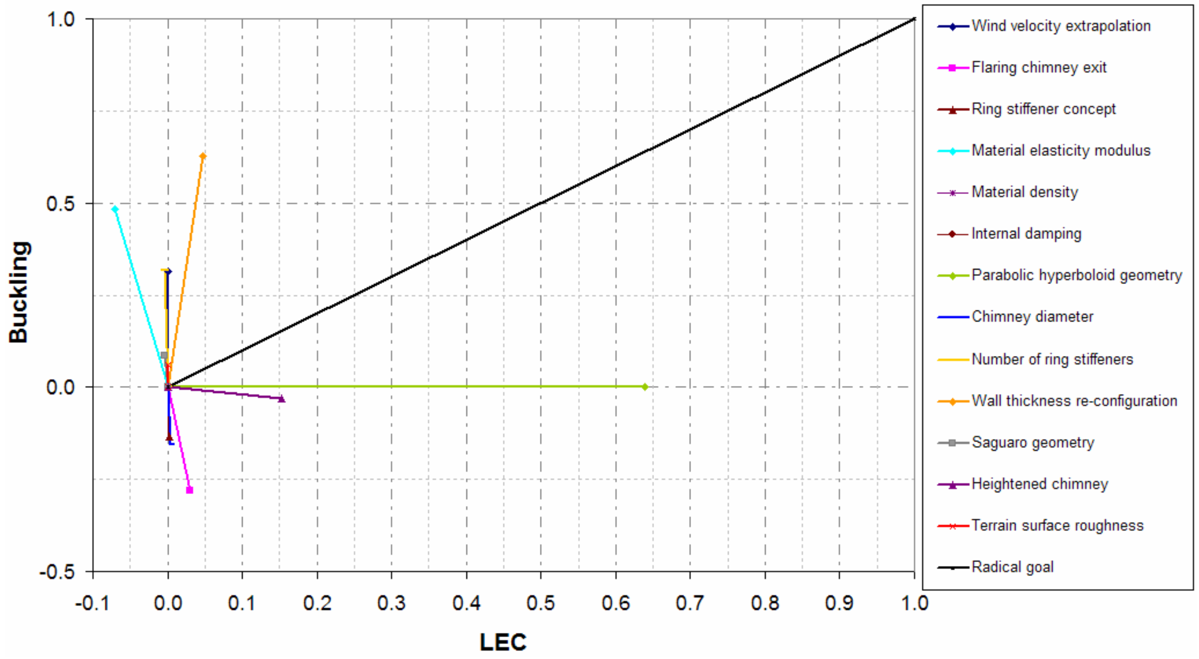

Figure 7-13. Vector approach portraying technology growth: buckling against LEC.

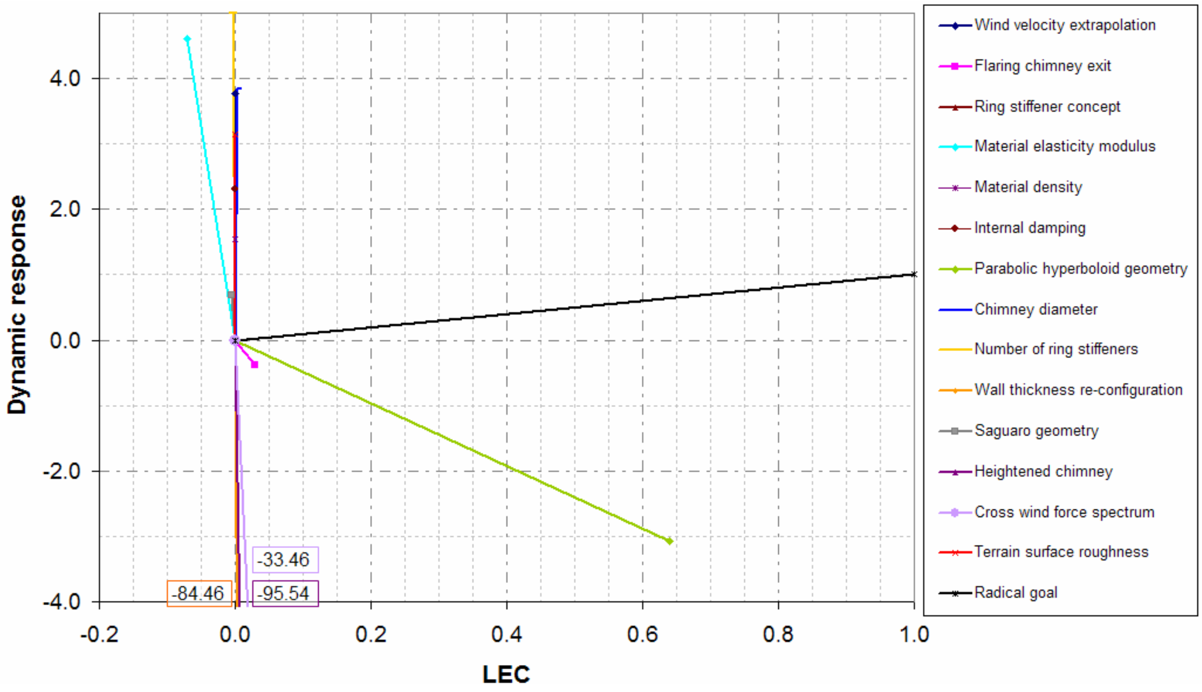

Figure 7-14. Vector approach portraying technology growth: dynamic response against LEC.

Buckling portrayed against dynamic response performance in Figure 7-15 yields a few technologies in the favourable quadrant due to the correlation between their structural functions. Material elastic modulus, wind velocity extrapolation and terrain surface roughness score well in the response criterion and moderate in the buckling criterion thereby moving toward the ideal result. The number of circumferential stiffeners and Saguaro geometry portray moderate growth toward the ideal result. The wall thickness re-configuration and increased chimney height again portray adverse growth (in terms of the currently discussed criteria). The implementation of the smaller cross wind force spectral value could decrease the adverse dynamic response in the increased chimney height alternative by almost three times.

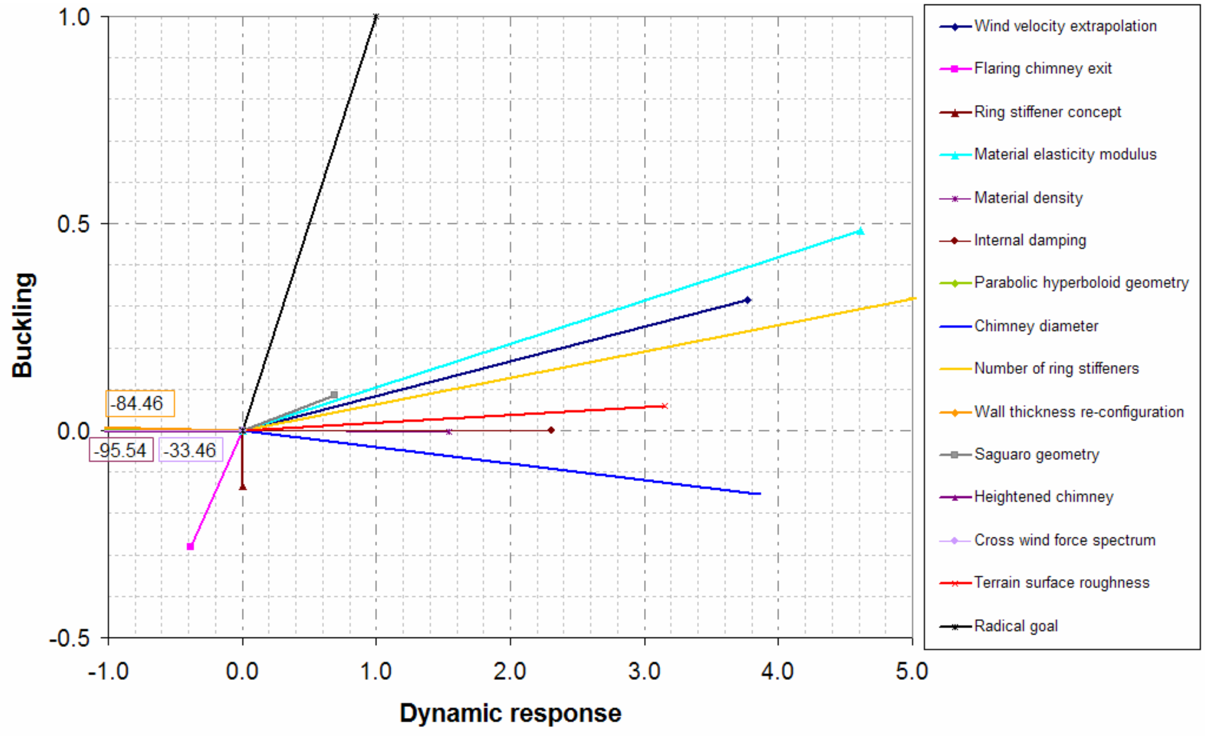

Figure 7-15. Vector approach portraying technology growth: buckling against dynamic response.

The vector visualisation approach could provide better visualisation (for this case, where there are only three performance measurement criteria) if all dimensions could be represented simultaneously in a three dimensional representation. The more dimensions presented (efficiently), the more information can be conveyed in a single glance.

## 7.4 Identification of critical technologies

Core technologies are distinguished from those that have less potential impact on system performance; non-contributing technologies are filtered out. Several conclusions can be made from the results, pointing toward specific technologies of potential critical influence. There are several technologies that do not yield satisfactory improvement to justify resource expenditure to develop and implement them. Others show significant to extremely significant improvement. The next paragraphs identify these technologies.

The most significant technology improvement in terms of cost reduction is the incorporation of parabolic hyperboloid geometry in the system. The large cost reduction lower limit and relatively small impact on structural performance (moderate adverse dynamic response) weighs heavy in favour of this technology incorporation.

Four technologies are distinguishable on the grounds of their contribution to mitigating low buckling modes. The wall thickness re-configuration may prove critical if adverse dynamic response can be mitigated. Material elastic modulus improvement has significant impact on structural integrity with moderate adverse cost impact. The better characterisation of wind turbulence model displays positive structural impact with no implications for the LEC. Finally, the implementation of more circumferential stiffeners, coupled with the realisation of its concept may improve buckling performance.

There are several technological alternatives meeting the ideal requirements when concerning the dynamic response. This criterion proves to be fairly straight-forward to accommodate in design and it does not require critical R&D toward chimney realisation. Still, it is noteworthy to identify the wind extrapolation and material elastic modulus as portraying significant impact, with the chimney diameter and the terrain surface roughness also showing favourable results. Wall thickness re-configuration and increased chimney height yield adverse dynamic response.

Several technologies remain insufficiently characterised. Cable stiffening and external damping devices promise potential alleviation of dynamic resonant modes at a relatively small cost increase and no impact on the energy yield. A directionally designed structure that promises a structure intelligently designed to circumferentially adapt to local weather prevalence could further decrease costs.

## 7.5 Concluding discussion

This chapter formulated conceptual technological alternatives and stipulated the criteria on which their impact on system performance was assessed. Performance results were calculated for comparison and identification of critical technologies. The core technology priorities, based on their impact on system performance, are summarised in this section. The chapter concludes with a brief summary of the results and a discussion of the models used in RIM applications, based on experience gained from its application on the SCPP chimney.

### 7.5.1 Technologies for consideration during further Radical Innovation Methodology phases

Without having yet performed the phase of the RIM where technology maturity and growth potential is determined, the following points can be made from the system performance evaluation results.

Five technologies are distinguished on the grounds of their impact on system performance. These are:

- the parabolic hyperboloid geometry,
- wall thickness re-configuration,
- material elastic modulus,
- the more accurate characterisation of the wind extrapolation model and
- the number of circumferential stiffeners.

The under characterised technologies (cable stiffening, external damping and the notion of directional wind based detail design) could significantly impact the chimney performance.

The results of the vector based visualisation prove that the technologies are seldom successful in satisfying all criteria or to engage the most favourable criteria quadrants. Further conceptualisation must aim to solve the contradictions identified in the vector based representation in order to move technological achievement into the favourable sectors.

### 7.5.2 Discussion of model, data quality and visualisation

The representation of reality through a model contains inherent loss of information through simplification, shortcomings, uncertainties and assumptions. The model must be representative within reasonable resource deployment. Critical failure modes must be represented. The more resources that are deployed the more insight and characterisation of the radical problem is gained; with possible consequential improvement in results.

Although a model must represent and accommodate as many as possible of the failure modes, the most important aspect of systems based conceptualisation/design – and model set up – is the comprehensive approach toward improving the *awareness* and understanding by the decision maker of all aspects of the system, and their impacts on various criteria/perspectives. This is not always quantify-able but may remain qualitative.

Comprehensive data quantifying *all aspects* of the system behaviour will seldom be acquired. This can be subdivided in two areas.

Firstly, the data itself may be unavailable or inadequate and only additional, focussed resource allocation may generate the necessary data to yield significant, quantitative answers in the evaluation process. As data is acquired or generated it can simply be imported in the current evaluation model; the model can be revised as needed in order to form a better representation of actual impact of technologies on the system.

Secondly, simplifying assumptions in modeling capabilities carry an inherent loss of data – complex theory cannot be readily incorporated in robust models. It is of critical importance that the user of the model is *aware* of the shortcomings of the model and interprets results accordingly.

Further, note that technologies that are not quantified (external damping, cable staying and directional design) are excluded from this representation.

### Efficient visualisation methods

Numerous alternate visualisation methods exist to convey information. The ones considered most appropriate for the SCPP specifically were used here. Others may be more appropriate for other RIM applications, and should be sought out and tailored.

The next chapter reports the technology assessment process of the technologies determined as critical in this chapter. This entails the characterisation, classification, trend identification and determination of R&D risk of the technologies identified according to the guidelines specified in section 4.1.4.

# CHAPTER 8

# TECHNOLOGY ASSESSMENT, TREND IDENTIFICATION AND RESEARCH AND DEVELOPMENT RISK OF CRITICAL SCPP CHIMNEY TECHNOLOGIES

In the previous RIM phases the SCPP chimney reference case was broken down to its essential technologies through functional allocation, failure mode identification and technology scan. These technologies were explored in sufficient detail and subsequently evaluated to determine their potential impact on SCPP chimney system performance. A few technologies emerged as critical toward achieving radical improvement of chimney system performance.

This phase of the RIM provides approaches and tools for handling the functional uncertainties identified in the technology identification phase. In incremental innovation codified procedure and field theory provide sufficient insight for the development process; radical innovation does not have this luxury – the uncertainties are functional in nature and not parametrical. The current chapter furthers the RIM with the assessment of technologies – in characterisation, classification and trend identification steps – to better grasp the characteristics and maturity (i.e. growth potential) of technologies in the system. This leads to knowledge of the potential benefit of technology improvement to the system performance. Expert input provides the technology manager with cutting edge technology trend information. R&D risk is determined for each technology alternative.

## 8.1 Characterisation of technologies

The technology characteristics frameworks describe the inherent characteristics of technologies (section 3.3). The previous chapter provides an evaluation of the technologies from a physical performance perspective; and the vector based visualisation aids the technology manager to determine what performance is required from a technology to satisfy the user defined criteria. The current section describes the technologies in terms of their inherent characteristics in order for the technology manager to know which progressions and acquisitions in technology would aid the system.

Table 8-1 displays the information of the characteristics for all identified system technologies in terms of the basic feature characteristics stipulated by the STA (section 3.3). The table deals first with the identified core technologies, then with the under-characterised technologies and concludes with the technologies that were determined to perform poorly during system performance evaluation in Chapter 7.

Table 8-1. Framework of Basic Features for the SCPP chimney.

| **Characteris-tic** | **Function** | **Principle of operation** | **Performance** | **Structure** | **Fit in system hierarchy** | **Material** | **Size** |
|---|---|---|---|---|---|---|---|
| **Five top technologies** | | | | | | | |
| **Parabolic hyperboloid geometry** | Inherent geometrical stabilisation; transfer of forces to foundation | Doubly curved shape displays inherent stabilisation properties; economically efficient use of material | Refer to section 7.1.10. Large success through this concept. Note: no specific concept optimisation was done | Positioned in region requiring stability; cooling tower shape of sufficient thickness to resist buckling, quasi static loads and contain reinforcement | Chimney tube → structural integrity → longitudinal stiffening | Reinforced concrete, i.e. compression and tension resistant composite; buckling resistant | Order of 100 m (diameter) |
| **Wall thickness re-configura-tion** | Stabilisation of geometry while adhering to all limit state criteria; containment of reinforcement | Design against geometry related localised and global buckling modes; leaving enough space for reinforcement containment | Refer to section 7.1.13. Note: No specific concept optimisation was done | Chimney shell thickness configuration | Chimney tube → structural integrity → circumferential stiffening | Reinforced concrete; i.e. compression and tension resistant composite; buckling resistant | Wall thickness of between 0.18 and 1.95 m |
| **Material elastic modulus** | Governs structural stiffness | Improvement of tendency of concrete to deform elastically under loading. | Refer to section 7.1.8. Note: No specific concept optimisation done; the maximum as found in literature chosen | Material characteristic determining stress-strain behaviour | Chimney tube → structural integrity → improved material characteristic | Reinforced concrete; could be another (higher elasticity) material | Micro material structure |
| **Wind velocity extrapola-tion model** | Describes gusting in the thunderstorm related wind | Mathematical formulation based on statistical data | Lack of sufficient measurement methods/resource hinders accurate quantification of thunderstorm gusts | Wind based action determining design loads and structural response | Fundamental theory | N/a; air-based turbulence, fluid dynamics in meteorology | Macro-scale turbulence model in adiabatic boundary layer |
| **Number of circumferen-tial stiffeners** | Added stabilisation against buckling and ovalling, circumferential stiffening | Cables in tension when shell experience external suction; more stiffeners = more stability | Typically diminishes deformation by one order. | Schlaich/Kratzig cable-stiffening concept | Chimney tube → structural integrity → circumferential stiffening | Presumably structural steel or carbon fibre | Cross sect'l area depends on forces; spans chim inner area, max length of 160 / 200 m |
| **Insufficiently investigated technologies** | | | | | | | |
| **Cable support** | Stabilisation against | Tensile resistant material connected | Great success in telecom towers | Set of cables designed to | Chimney tube → | Mild or high strength steel, | Cables spanning |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **adding lateral stiffness** | buckling and resonant response | to shell upper regions, fastened at zero level, providing additional support | and other slender structures; investigation to SCPP chimney indicates potential | provide necessary lateral stiffening | structural integrity → lateral stiffening | polyester or synthetic fibres | between 680 and 1273 m; significant thickness |
| **External damping devices** | Mitigation of resonant vibrations | Inertia of great mass is balanced by comparatively lightweight structural component | Although increasing use in high-rise buildings, applicability to SCPP chimney remains uncertain | Several concepts exist: Tuned Mass Dampers consists of counterweight mass mounted using massive spring coils or hydraulic dampers | Chimney tube → structural integrity → external damping | Many concepts exist utilising fluids and solids | Percentage of vibrating mass; 2-4% in wind turbines [Faber] |
| **Directional design** | Optimise design to reduce costs | Use statistical wind directional data for radial state limit design | N/a | Optimisation of shell, transfer section and foundational geometry | Chimney tube → structural integrity → directional design | N/a | Design approach applies over full scale of chimney, also foundation |

**Low scoring technologies**

| Characteris-tic | Function | Principle of operation | Performance | Structure | Fit in system hierarchy | Material | Size |
|---|---|---|---|---|---|---|---|
| **Wind direction variations over chimney height** | Investigate load cases due to directional variation in wind profile over height | Use statistical wind directional data to set up load cases | Robust investigation by Rousseau [2005] indicates excitation of higher SCPP global vibration modes. | Definition of load cases | Fundamental theory | N/a | Design approach applies over full scale of chimney |
| **Applicabil-ity of prescribed critical buckling factor** | Investigate applicability of critical buckling factor on SCPP chimney | Perform non-linear buckling analyses incorporating initial displacement and imperfections to translate to linear elastic condition | N/a | Definition of critical buckling load factor | Fundamental theory | N/a | Design approach applies over full scale of chimney |
| **Cross wind force spectrum** | Characterisa-tion of cross wind spectral values corresponding to natural frequency | Characterisation of cross wind force spectral values exerted on structures due to lateral air movement | Refer to section 7.1.4. | Wind based action determining quasi static design loads | Fundamental theory | N/a | Size of structure |
| **Flaring of chimney exit geometry** | Decrease exit pressure losses | Flaring enlarges inner area close to chimney exit and reduces kinetic energy loss | Energy yield increases slightly but semi-localised buckling lowers significantly | Quadratic enlargement of area chosen with wall thickness as for reference case | Chimney tube → optimal airflow channel → flaring | Reference case materials | Doubling of exit area |
| **Chimney inner surface treatment** | Reduction of inner surface friction losses | Smoothening of inner surface to reduce friction losses by surface treatment | Change in energy yield is negligible | Surface friction is decreased by some surface treatment | Chimney tube → optimal airflow channel → surface friction | Specified friction surface treatment | Chimney surface |
| **Circumfe-rential stiffener concept** | Decrease in circumferential stiffener pressure loss coefficient through alternative concept | Decreasing concept solidity decreases aerodynamic drag losses | Exact values n/a. Typically yields higher energy but lower buckling values/natural frequencies. Kratzig concept proves to work best | Assumed concept: half the number of braces of that of the reference case implemented | Chimney tube → structural integrity → circumferenti al stiffening | Presumably structural steel or carbon fibre | Cross sectional area depends on forces; spans chimney diameter |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Material density** | Decrease mass in upper region of chimney toward lower natural frequencies | The mass contribution by the upper region decreases → less activation of these parts to vibration; lower density through air entrainment/ low density aggregate | Decrease in global natural frequency with adverse impact on buckling resistance | Lower density aggregate with more air entrained in concrete | Chimney tube → structural integrity → improved material characteristic | Presumably reinforced concrete; additives or other material may prove useful | Material level, with macro impact |
| **Material internal damping** | Decrease in dynamic structural response | Change in material matrix/substance to achieve higher damping ratio | Refer to section 7.1.8. | Fibres or other additives to increase damping ratio | Chimney tube → structural integrity → improved material characteristic | Concrete variant e.g. fibre-reinforced concrete | Material level, with macro impact |
| **Increased chimney diameter** | Increase energy output and 1st global natural frequency | Larger enclosed volume form larger pressure differential; Larger diameter = increased cross sectional resistance to bending; | 1st global natural frequency higher; semi-localised buckling persists, along wind response slightly lower | Increase of diameter; wall thickness change over height assumed to remain as for reference case | Chimney tube → structural integrity → longitudinal stiffening | Reference case materials | Order: 100 – 250 m diameter |
| **Wind-structure interaction manipula-tion: Saguaro geometry** | Saguaro geometry significantly decreases circumferential pressure distribution peaks; potential structural resistance | Manipulates turbulence and vortex separation; geometry realised from non-structural or structural | Reduces suction peak from $C_{pe} \approx 2.5$ to $C_{pe} \approx 1.0$ | Saguaro geometry ribs constructed from non-structural material, e.g. membrane or reinforced concrete | Chimney tube → structural integrity → manipulation of wind-structure interaction | Membrane or structural material e.g. reinforced concrete | Situated from mid to upper regions of chimney; Rib radius = $1.14 \times D_{chimney}$ |
| **Increased chimney height** | Increase energy output | Larger enclosed air volume and lower pressure at tower tip form larger pressure differential between inside and outside | Increases in energy weighed with significant decrease in global free vibration frequency | Elongation of current chimney geometry; assume wall thickness to remain constant | Energy yield increase | Reference case materials | 220 m added in height |
| **Terrain surface roughness** | Choice of optimal site from terrain roughness perspective | Surface roughness coefficient significant in wind extrapolation model. Optimal terrain impacts wind load and turbulence | Refer to section 7.1.18. | Wind based action determining quasi static design and buckling loads | Chimney tube → structural integrity | Earth surface manipulation / Fluid | Micro into macro level |

The investigation of the technological characteristics observes aspects serving as a basis for subsequent technology acquisition, for example, the fact that not many technologies are primarily directed to mitigate SCPP chimney costs (conceptual thinking along this impetus may yield cost mitigating technologies). Problem solving specifically aimed at solving contradictions can be combined with other technological insight to approach challenges in a fresh, lateral manner.

The Framework of Basic Features characterises the type of system and possible solutions (similar technologies identified through a taxonomical perspective). Development for setting up such a taxonomical structure – reported in the next section – could aid radical innovations such as the SCPP chimney toward pro-actively searching for solutions rather than having to wait for chance and semi-structured problem solving methods to direct R&D strategy.

## 8.2 Technology taxonomy

The SCPP chimney and its systems are classified by way of the Nine Cell Technology Functional Classification Matrix (section 3.3.2) on the hierarchy levels identified in section 6.4 (Figure 6-5) in order to sort it relative to other technologies for discovery or identification of similar potentiall influential technologies.

The chimney is, at the highest level, a functional entity responsible for conveying (*transporting*), air (*matter*) from the collector centre to the lower pressure mid tropospheric layers.

### 8.2.1 Level 2 – foundation and chimney-to-foundation transfer systems

The foundation system and its Level 3 functionalities *store, transport* and *process* transferred loads (*energy*) to the substrate. The chimney-to-foundation transfer system and its Level 3 and 4 functionalities facilitate initial *transport* of air (*matter*) moving from the collector to the chimney base. Further, it transfers loads to the foundation. As stated in section 6.4, this dissertation focuses on the innovation of the *chimney tube*.

### 8.2.2 Level 2 – chimney tube system

The tube system is responsible for upholding the through-flow channel, i.e. keeping the basic tube shape without significant internal obstructions. It *transports* air (*matter*) through the tube and *stores*, *transports* and *processes* incoming kinetic wind *energy* into mechanical and potential energy which is dissipated through damping or transferred to the foundation of the chimney and away from the system.

The tube system consists of two Level 3 subsystems that can be classified individually: optimal airflow channel and structural integrity.

#### Level 3 – optimal airflow channel

The airflow system *transports* air (*matter*) from lower parts of the tube to upper parts with the proposed diffuser, tube and flaring geometry *processing* the kinetic *energy* to be high at the turbine position for optimal force on the turbine blades. Deceleration of air before the exit minimises exit losses. The Level 4 systems – flaring, surface friction, aerodynamic shaping of flow obstructions and chimney height increase – advance those functionalities.

Level 3 – structural integrity

The main function of the chimney – being a cost efficient, structurally sound prismatic shape for channelling movement of air – is supported by structural technologies and enhanced through stabilisation systems increasing its structural integrity. The Level 4 systems classifications are as follows:

Improved material characteristics, higher longitudinal and circumferential structural stiffness, geometrical stabilisation and the wind-structure interaction manipulation cause the system to absorb and *process* less of the kinetic wind *energy* into deformation and high vibration frequencies with coinciding modes. When functioning properly these technologies could assist avoidance of global structural deformation both under quasi-static and dynamic wind loading. This could mitigate or circumvent high localised internal energy caused by strong localised deformation, and transfer internal energy into the global structure leading to favourable global deformation in resistance to loading action.

The potential damping contribution of an external damping device is a temporal, delayed reaction *energy storage* mechanism which releases the energy at the tuned instant.

The Saguaro geometry manipulates the wind–structure interaction to absorb and *process* less of the kinetic wind *energy*.

Directional design optimises the structure to perform at limit state criteria *processing* the kinetic wind *energy* optimally toward achieving cost reduction.

Table 8-2 displays the Nine Cell Technology Functional Classification Matrix containing the SCPP chimney systems up to the fourth level. The SCPP chimney and its subsystems fulfil the functions of processing and transferring load-based energy while transporting air-matter arriving from the chimney-to-foundation transfer system into upper air regions. Damping systems temporarily store energy. Chimney subsystem technology functionalities operate in four cells of the matrix: transporting matter and processing, transporting and storing energy. Systems fulfilling similar functions can be compared to SCPP chimney technologies for their potential acquisition in the chimney system with aid from this technology classification framework.

Table 8-2. Nine Cell Technology Functional Classification Matrix classifying the SCPP chimney systems to the fourth level. The systems level is indicated in brackets.

| | | **Ways of handling** | | |
|---|---|---|---|---|
| | | **Process** | **Transport** | **Store** |
| **Aspects handled** | **Matter** | | Chimney system (1)<br>Tube system (2)<br>Chimney-to-foundation transfer (2)<br>Optimal airflow channel (3) | |
| | **Energy** | Foundation system (2)<br>Tube system (2)<br>Chimney-to-foundation transfer (2)<br>Structural integrity (3)<br>Material improvements (4)<br>Lateral stiffening (4)<br>Circumferential stiffening (4)<br>Manipulation of wind-structure interaction (4)<br>Geometrical stability (4)<br>Wind-structure interaction manipulation (4)<br>Directional design (4) | Foundation system (2)<br>Tube system (2)<br>Chimney-to-foundation transfer (2)<br>Structural integrity (3)<br>Circumferential stiffening (4) | Foundation system (2)<br>Chimney-to-foundation transfer (2)<br>Structural integrity (3)<br>External damping (4) |
| | **Information** | | | |

## 8.3 Identification of trends

Trend identification is performed to determine the maturity of the SCPP chimney system and subsystem technologies and award a rank to each investigated technology.

Figure 8-1 displays the life cycle stages along a technology S-curve (as example of a typical technology trend curve). A key for the ranks and a description thereof is provided in Table 8-3. Each technology for which trend identification was performed is briefly discussed; all technologies are subsequently awarded ranks. Although in this study this procedure is performed by the author alone due to resource constraints – further research must perform more thorough investigation of technology rankings – it suffices in illustrating the application of the RIM.

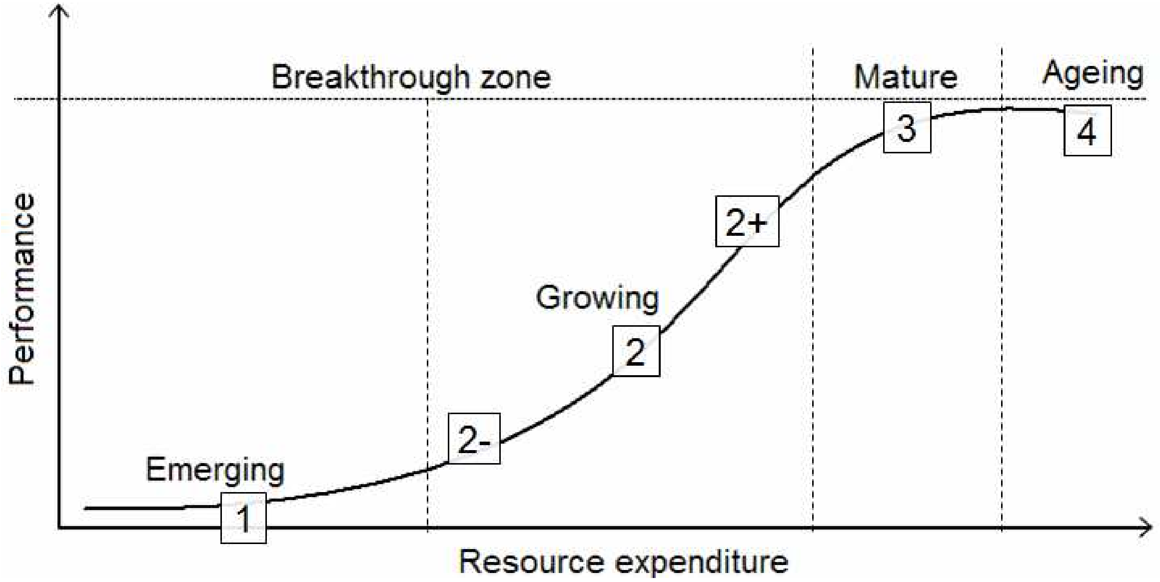

Figure 8-1. Technology S-curve displaying rankings.

Table 8-3. Key for technology trend status ranks.

| Rank | Description |
|---|---|
| 1 | Research initiates technology development; minimal supportive/parallel research efforts. |
| 2– | Increasing R&D activity; significant strides in performance improvement |
| 2 | Increasing amount of R&D; constant performance improvement |
| 2+ | Saturation of R&D effort; declining performance improvement |
| 3 | Additional research has little improvement on performance |
| 4 | Technology becomes obsolete |

The investigation is performed for the highest level SCPP and similar chimney structures, and on the five top technologies that emerged from the success evaluation procedure. Technologies that are under-characterised, but promise significant impact on the system (cable staying, external damping and directional design) also undergo trend identification in order to gain insight into their growth potential.

### 8.3.1 Solar Chimney Power Plant system

Firstly, the SCPP concept is investigated by a survey of SCPP system and SCPP chimney publications. Structural SCPP chimney performance characteristics are seldom quantified and cost models for the SCPP chimney differ significantly in literature, making it difficult to compare concepts and identify trends. Structural height trends are also investigated.

Number of publications over time

The number of publications on the topic of the SCPP and specifically the chimney structure is obtained through a literature survey. Figure 8-2 indicates the overall increase in number of publications per year, both for all scientific fields and structurally related fields.

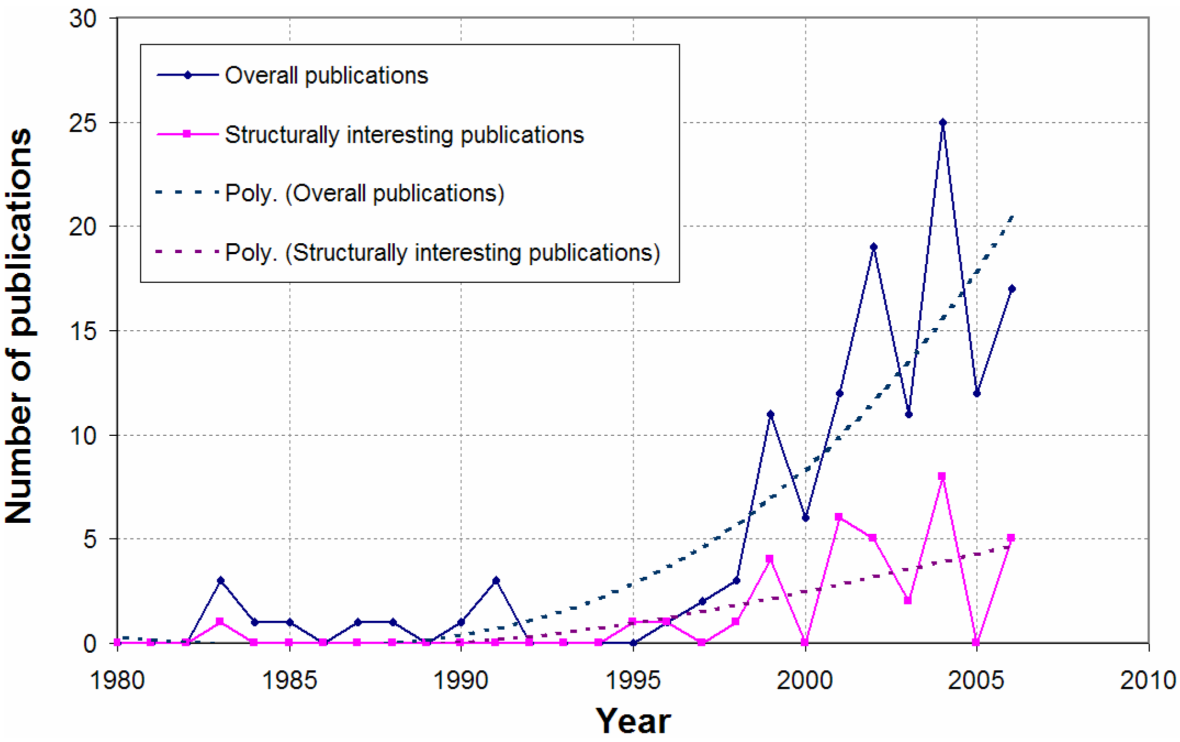

Figure 8-2. Number of SCPP publications.[i]

A growing trend in publications is identified which, apart from indicating the growing global interest in the concept, may be interpreted as reaching a phase of growth (refer to

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[i] The curves in the graphs in Chapter 8 termed "Poly" (in the graph legend) depict polynomial best-fit curves to the data points.

Figure 8-1 for the life cycle phases in the technology S-curve). The number of structurally inclined publications is also increasing, indicating growth in this area.

Trend in height of structures

Height, being the most representative parameter concerning structural challenges in the SCPP chimney concept, is investigated here in terms of its evolution. The history of height records of free-standing and cable-stayed chimneys, towers, masts and buildings [Wikipedia 2 2007] are depicted in Figure 8-3. A trend emerges predicting a gradual second-order increase in the height-to-year gradient; note that a height of approximately 800 meters is assumed for the Burj Dubai which is to be completed in 2008/9. Several proposed structures indicate a further increase in this gradient with proposed heights of 1,852 meters for the Al Jabar tower, Bahrain, 1,050 meters for a tower in Dubai, UAE, 1,022 meters for the Murjan Tower, Bahrain and 1,001 meters for a tower in Madinat al-Hareer, Kuwait [Wikipedia 2 2007].

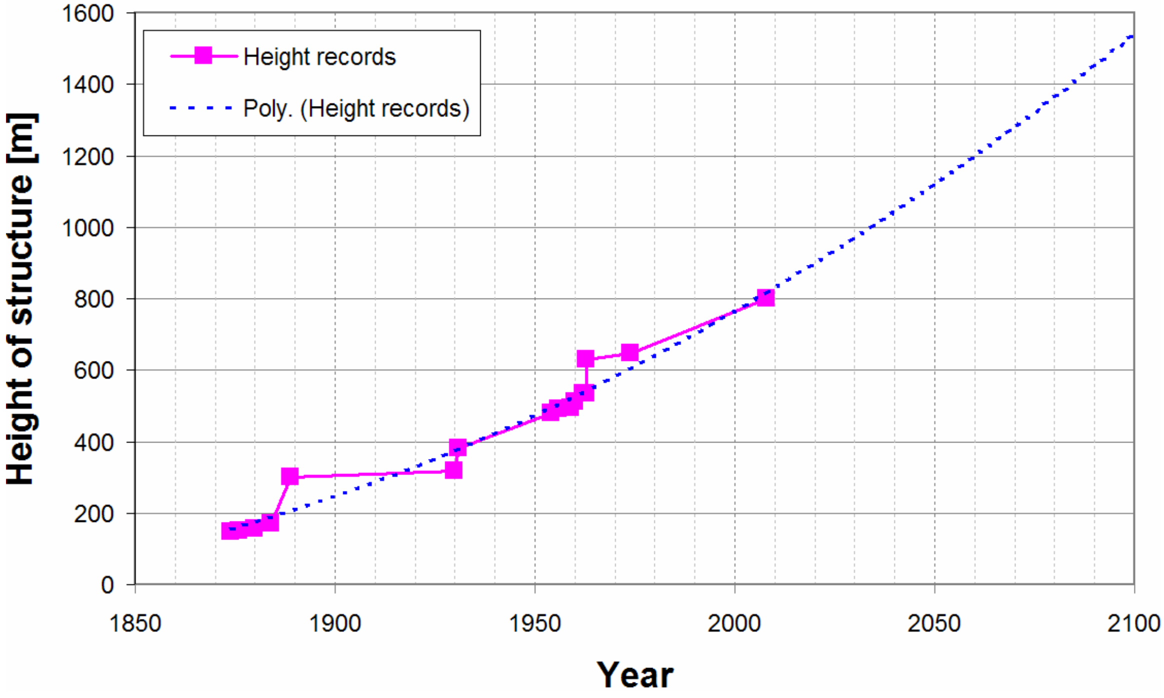


Figure 8-3. Extrapolation trend based on the tallest man-made structures over the past 150 years.

Extrapolation of the current trend as produced in Figure 8-3 predicts that by 2050 technology could enable structures to scale heights exceeding 1,100 meters and 1,500 meters around 2100. Note that these predictions are strongly susceptible to political and economical endeavour, for instance, the current rivalry in the Middle East for the prestige of show-casing the tallest structure in the world. Sustained urbanization of the world population with consequent space shortages could also provide powerful impetus toward building taller structures.

The chimney concept, in terms of its structural height, shows an overall upwards trend over time and is awarded a growing rank of 2– (positive curvature on Figure 8-1).

### 8.3.2 Parabolic hyperboloid geometry

Although the structural behaviour of doubly curved shells is well understood, mature and widely publicized, the mergence of parabolic hyperboloid geometry with general height requirements of chimneys, such as those needed in natural draught cooling towers, depicts a linear growing trend over the past decades. Figure 8-4 shows this trend on an extrapolation of cooling tower height chronology [Harte 2007]. The data points indicate how cooling tower design heights, optimised in terms of structural reliability and economic criteria, increased over the past century. On the basis of this trend it is envisaged that cooling towers will be constructed up to heights of almost 300 meters by 2050.

The structural and practical applicability of this technology to SCPP chimney geometry is currently under intense investigation by experts in cooling tower structures and reinforced concrete shells. If realised, this radical increase in height may represent a significant deviation from the linear trend – a radical leap in the capability of this technology from its projected growth.

Structural height of cooling towers, as a representative of the performance of parabolic hyperboloid shaped reinforced concrete structures, shows a growing, linear trend over time and is awarded a growing rank of 2 (linear on Figure 8-1).

### 8.3.3 Wall thickness re-configuration

The wall thickness configuration merely requires specific design and optimisation – no technological performance breakthroughs are expected. It is awarded the mature rank of 3.

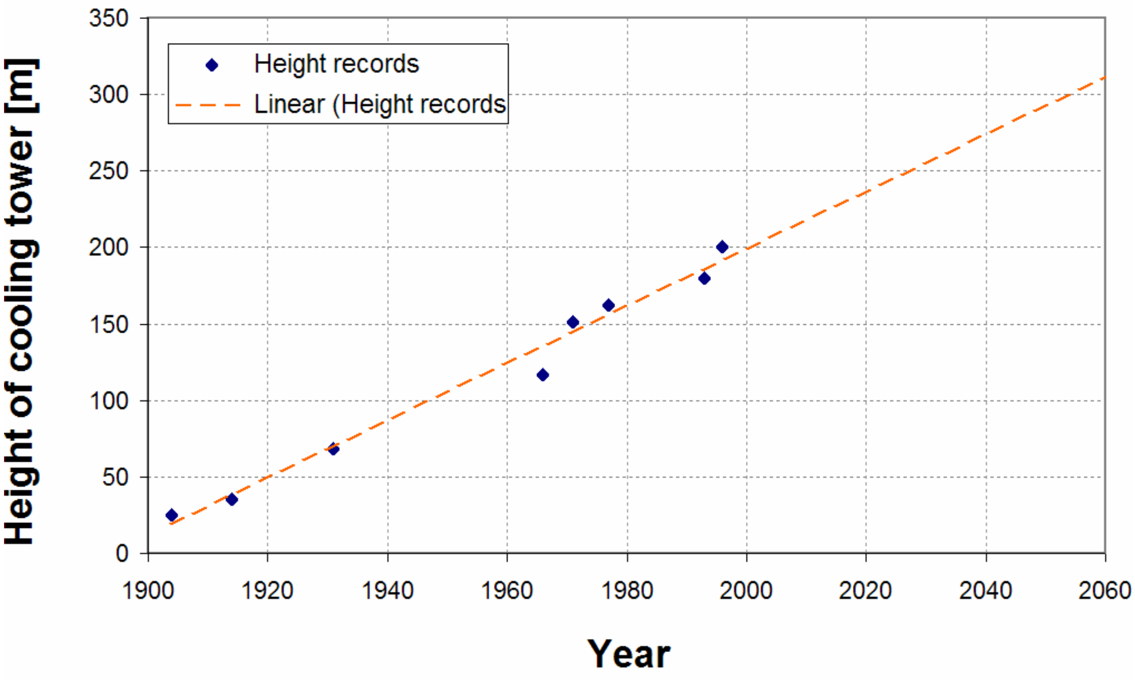


Figure 8-4. A linear trend fit to cooling tower (parabolic hyperboloid shaped) height increase over time.

### 8.3.4 Elastic modulus

Factors affecting concrete elastic modulus

In concrete – a heterogeneous material – the volume fraction, density and modulus of elasticity of the principal constituents, as well as the characteristics of their interfacial transition zone, determine the elastic behaviour of the composite [Mehta and Monteiro 2006].

The impact of constituents and their transition zones on the elastic modulus are briefly introduced. Aggregate with higher elastic modulus increases the concrete modulus of elasticity. Aggregate size, shape, surface texture, grading and mineralogical composition influences the micro-cracking in the interface transition zone and thus affect the shape of the stress-strain curve. The elastic modulus of the cement paste matrix is determined by its porosity, which is in turn controlled by the water-cement ratio, air content, mineral admixtures and degree of cement hydration. Capillary voids and micro-cracks are more common in the interfacial transition zone than in the paste matrix and play an important part in determining the stress-strain relations in concrete. Several factors control its quality of binding with the paste, i.e. water-cement ratios, mineral admixtures, aggregate size and shape, degree of consolidation, degree of hydration and the chemical interaction between aggregate and cement paste.

It is concluded that concrete elastic modulus is susceptible to a range of factors, each of which, in the light of the determined structural gain (section 7.4), could be optimised to achieve a higher elastic modulus. Consideration of an optimal choice of construction site, with favourable materials available on-site, is advisable to reduce costs.

## Concrete strength and elastic modulus trends

Conventional concrete is characterised as low, moderate and high-strength exhibiting strengths of less than 20, 20 to 60 and more than 60 MPa, respectively [Van Zijl 2008]. Figure 8-5 presents the view of a German cooling tower expert on growing trends in concrete strength [Harte 2007], predicting strengths ranging from 200 to 500 MPa. Developments in ultra-high strength concretes produced composites that confirm his view, with compressive strengths of between 200 MPa and 800 MPa, depending on the curing conditions (reactive powder concrete (RPC) contains a high fiber volume and is pressure and heat treated) [Mehta and Monteiro 2006].

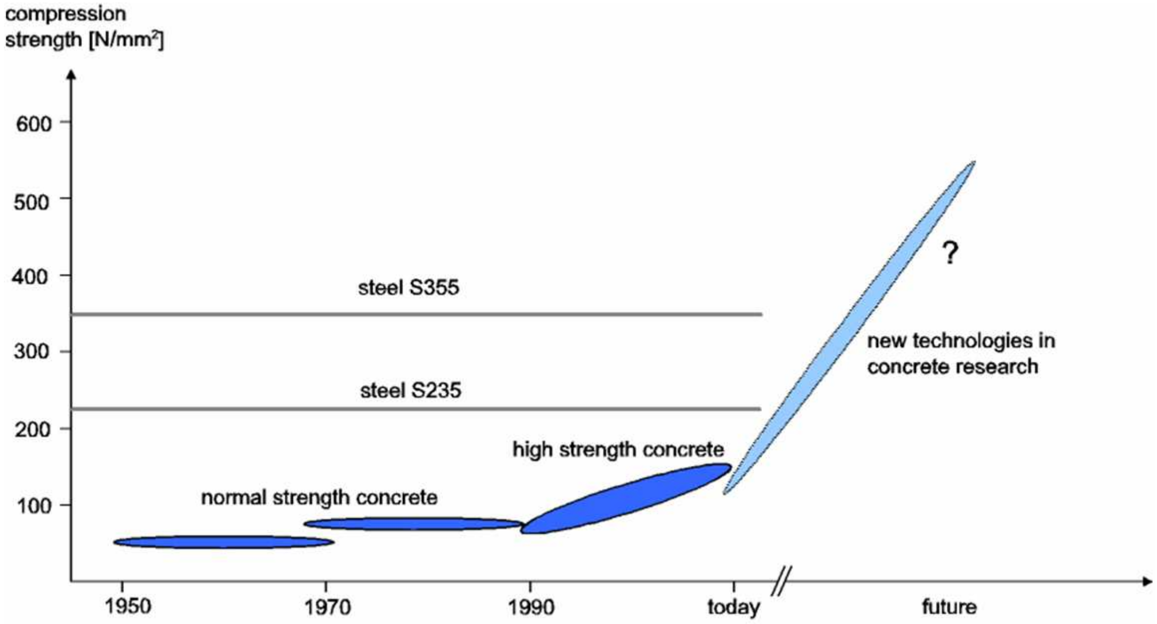


Figure 8-5. A view on developments in concrete strength [Harte 2007].

Normal weight and strength concretes exhibit a modulus of elasticity ranging between 21 and 34 GPa while high strength concrete has reached values of 47 GPa [Mehta and Monteiro 2006]. Literature reports elastic modulus values of 60 GPa for RPC (200 MPa strength) and values up to 70 GPa for slurry-infiltrated-fibered concrete (SIFCON – concrete containing 4–20% steel fiber content). No mathematical formulation for strength–elastic modulus curves exist for ultra-high performance concretes but Suksawang et al. [2006] determines the “Gardner”-formulation to be the best fit to high performance concrete experimental data. Figure 8-6 extrapolates the Gardner data with a power curve and compares it with data points for RPC and SIFCON. This investigation, however not directly applicable to ultra-high strength concretes, indicates a positive growth trend in elastic moduli toward values exceeding the augmented elastic modulus of 60 GPa (section 7.2.8).

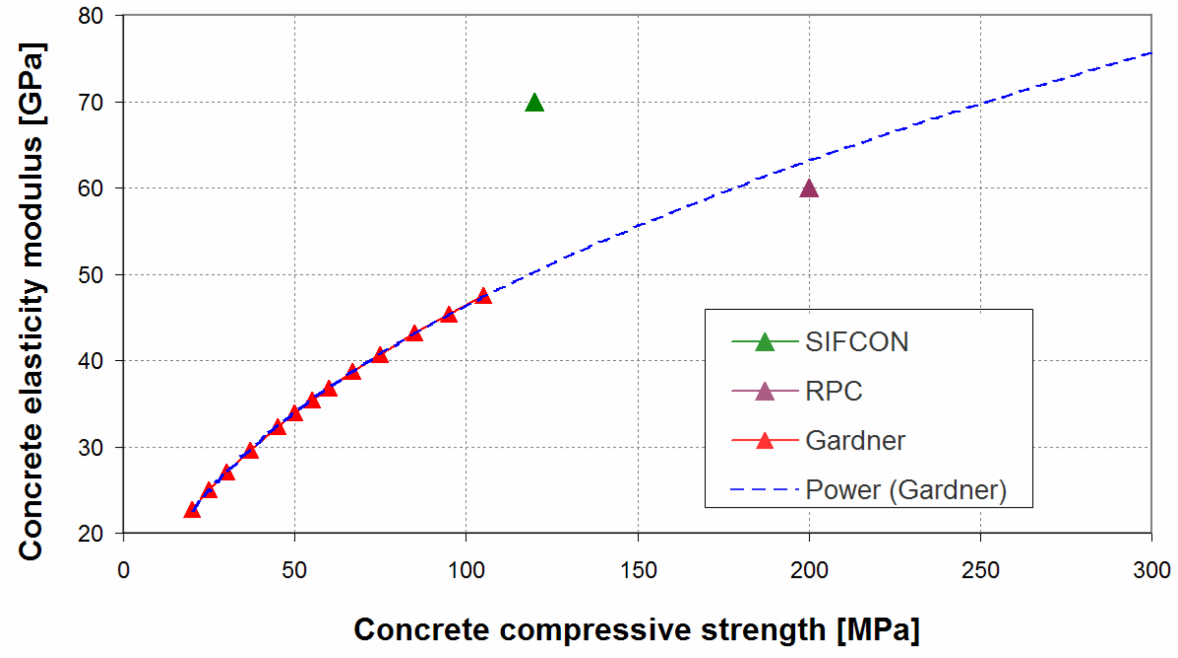


Figure 8-6. An extrapolation of the Gardner-formulation indicates a potential trend in future elastic moduli growth.

Current level of maturity

The physical limit of the elastic modulus of concrete is difficult to determine due to its composite nature. The current level of maturity of concrete elastic modulus is a function of development of its constituents and their interrelation; there is no easy way to measure something that has such aggregate, universal applications [Wunderlich and Khalil 2004]. Figure 8-6 suggests a period of growth lying ahead for concrete technology. Furthermore, technology replacement theory (refer to Section 3.6.1) suggests that sub-curves (the ellipsoids in Figure 8-5) underlie the overall concrete strength growth curve, indicating that the generation of normal concretes was replaced by a generation of high-strength and high performance concretes which is currently being replaced by a generation of ultra-high strength concretes.

A final note concerns the cost of these ultra-high performance concretes. The structural gain of these composites currently comes at significant financial costs (due to cost of high cement content, heat treatment, high fiber cost, construction related costs or combinations thereof) compared to traditional concrete structures. Therefore its implementation is generally restricted to specialised applications [Li 2000]. Still it is decidedly interesting to take note of such developments in material science with the aim of future incorporation. Cost trends may reveal further insight on the potential for large scale application of higher elastic modulus concrete in the SCPP chimney.

Concrete stiffness properties show immense potential for improvement. Although concrete material technology has been the subject of a large amount of research and performance improvement, the rise of ultra-high strength concretes introduces a new technology growth era; this technology is awarded a growing rank of 2– (positive curvature on Figure 8-1).

### 8.3.5 Wind velocity extrapolation profile

Turbulence models currently implemented in wind loading standards are based on frontal weather systems. Section 7.1.1 introduced a discrepancy between international codes [ISO DIS 2008] and meteorological conditions [Milford 1987] at Sishen. Further investigation into wind velocity profiles reveals that an altogether different weather system may provide a governing load case for the SCPP chimney, i.e. thunderstorms.

Increasing focus on the characterisation and physical simulations of thunderstorms and their downbursts is evident from literature over the past decades, presumably due to reports of the importance of thunderstorm generated winds as *design* wind events. Re-analysis of extreme gust wind speeds in Australia indicates half of their occurrence due to thunderstorm events, while gust wind speeds in the United States indicate as many as one third of extreme winds occurring through thunderstorms [Letchford et al. 2002]. Subsequent discussions led to the recommendation that Wind Engineering must focus more resources on the fundamental issue of the flow structure of extreme winds.

Wind generated by thunderstorms is characterised by a lower mean with higher deviation (gust) at higher frequencies [Holmes 2001] than winds from frontal weather systems. This characterisation of thunderstorms resembles the wind data from Sishen – low mean wind velocity with high three second gust velocities. Downbursts generate strong horizontal gust winds with turbulence upon hitting the Earth surface. Figure 8-7 depicts a typical thunderstorm velocity profile [Kim and Hangan 2007] and a frontal velocity profile – thunderstorm profiles differ significantly from that of frontal systems with lower velocities in the upper regions; the main region of SCPP susceptibility to wind excitation.

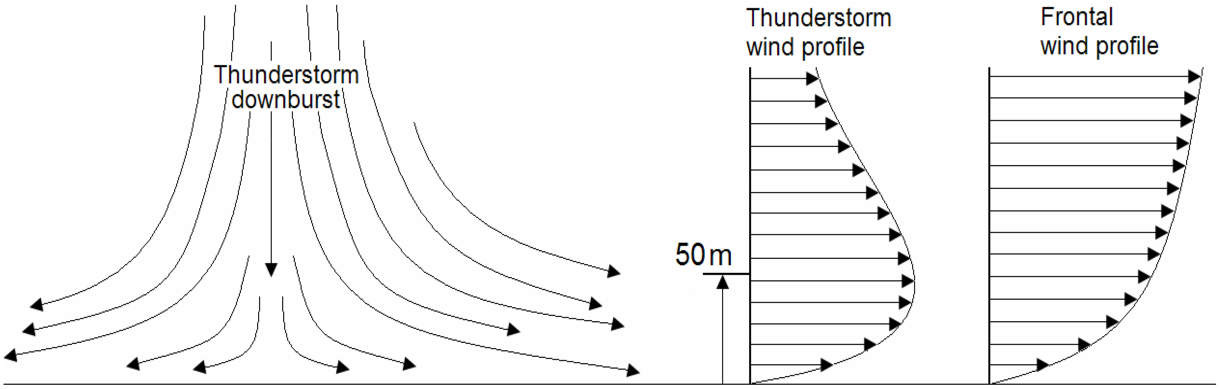


Figure 8-7. Schematic view of a downburst depicts the thunderstorm profile in comparison to a frontal profile [based on Kim and Hangan 2007].

Number of publications over time

The trend toward complete characterisation of thunder storm turbulence and its incorporation in design codes is investigated here, without going into too much field specific detail. The publications-over-time metric is investigated to determine trends in the development in characterisation of thunderstorm behaviour. A brief familiarising investigation reveals keywords for a literature survey: "thunderstorm", "downburst", "downdraft", "micro-burst", "macro-burst" and relevant instances of "extreme wind". Most of the publications concern the characterisation of thunderstorm phenomena with several addressing the modeling of these phenomena. Publications were scanned for relevance and the number of “hits” plotted in Figure 8-8. A significant increase in publications is noted, especially in the last two decades. A second order polynomial curve is fit to the data points to estimate the maturity of the knowledge basis, assuming it to be a function of the number of publications [Savransky 2000].

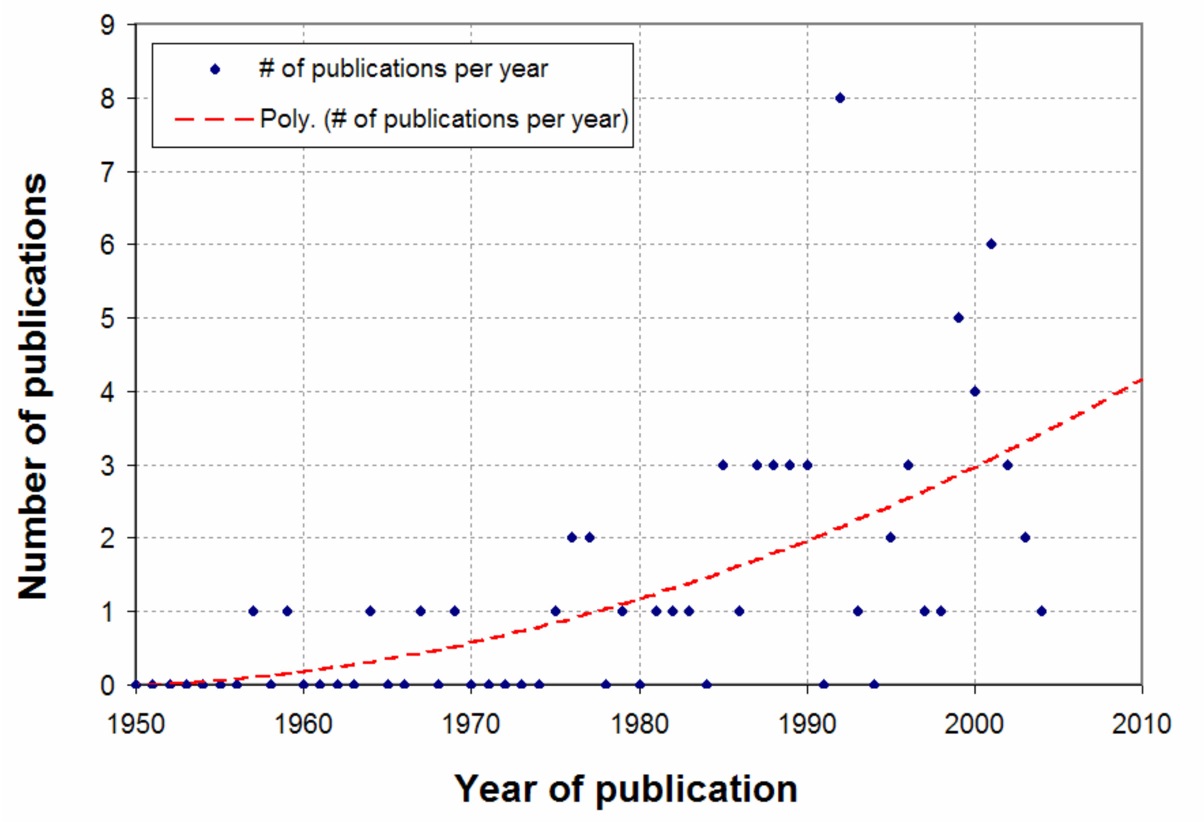


Figure 8-8. Thunderstorm related publications over time.

Incorporation in design standards

The incorporation of thunderstorm based extreme wind characteristics in design standards depicts an important trend, i.e. the standardisation of knowledge. Literature agrees that thunderstorm activity contributes significantly to extreme wind data, therefore the understanding of the physical phenomena, modeling, characterisation and subsequent incorporation in design standards should logically follow. The Joint Committee on Structural Safety was the first design code to mention thunderstorms as a specific design case (dated 2001) [JCSS 2001] and, more recently, the updated ISO code actually provides terrain roughness and height exposure factors for peak wind speeds for thunderstorms [ISO DIN 2008]. These developments indicate the increasing certainty and maturity with which scientists relate to thunderstorm based wind action.

Design for dynamic action that is based on mean wind velocity profiles and subsequent gust velocity description, e.g. the gust factor (the ratio of peak gust velocity to mean wind velocity – Appendix B equation B3), have to be re-interpreted for a thunderstorm load case. The significantly differing turbulence structures for frontal and thunderstorm weather systems require adaptive design methods.

The number of publications shows an emerging trend implying the increasingly sound understanding and characterisation of thunderstorm turbulence with a significant indicator of conclusiveness in the acceptance of turbulence data in the most recent ISO code. The basic characteristics of thunderstorms are understood and only region specific implementation of this knowledge is required; this technology development is awarded a growing rank of 2+ (negative curvature on Figure 8-1).

### 8.3.6 Circumferential stiffener concept

The number of circumferential stiffeners proves to have a significant impact on structural behaviour; its obstruction of through-flow area and additional cost, however, has an adverse impact. The trend toward efficient circumferential stiffening, i.e. maximum circumferential and radial (to prevent ovalisation) stiffness with low through-flow obstruction and cost is investigated here. It is arduous to describe the technological maturity of circumferential stiffeners in terms of performance due to its limited and simplistic use in reinforced concrete shells; consequently the technology landscape is scanned to search for similar technological concepts in order to grasp its maturity and learn of similar solutions. Some clues are discovered in nature and from industry.

The concept of low solidity circumferential stiffeners has limited descriptions and application in literature and industry; the concept of bracing a chimney structure by a flow-obstructing measure, as proposed by Schlaich [2004b] is unknown (chimneys typically necessitate optimal through-flow).

Complete through-flow stiffening ring: cooling towers

Cooling towers could deploy one or several external stiffening rings [Bosman et al. 1998] along the height of the structure to strengthen it along the circumference – see

Figure 8-9 [Internet 4 2008]. Although this cross sectional enlargement of the shell is relatively inexpensive and does not pose a large obstacle to through-flow it was found to be insufficient for the scale of SCPP chimney application [Lourens 2005].

Figure 8-9. Circumferential stiffening rings in cooling towers [Internet 4 2008].

High solidity stiffening ring: bamboo stiffening

The bamboo plant, a self supporting, high aspect ratio natural structure, exhibits regular solid sectional stiffening discs (Figures 8-10) playing a significant role in its structural integrity. The nature of the SCPP chimney circumferential stiffener technology poses a unique challenge of creating a high stiffening-to-solidity ratio, i.e. providing significant rigidity to the structural cross-section with only slight cross-sectional obstruction. Bicycle wheels propose such a solution.

Low solidity stiffening: bicycle wheel

A modern bicycle wheel (Figure 8-11) consists of a metal hub, wire tension spokes and a metal rim which accommodates a pneumatic tire. A load applied at the hub causes the wheel to flatten slightly near the ground contact area. The rest of the wheel remains approximately circular by tension increase in all of the spokes except for the few in the flattened region.

Figure 8-10. Bamboo revealing internal stiffening structures.

Figure 8-11. Typical bicycle wheels.

SCPP bicycle wheel stiffening concept

Structural research shows that it is efficient to stiffen the SCPP chimney shell at several levels with cables arranged like bicycle wheel spokes within the chimney [Schlaich Bergermann und Partner 2004] as depicted in Figure 8-12. This concept could reduce meridional stresses in the SCPP chimney to an extent that tension disappears completely making high chimneys feasible. Schlaich proposes these structures as the “only really new feature of [*SCPP chimney*] compared to existing structures” [Schlaich et al. 2004a].

The spoked wheel allows relatively unhindered air flow (refer to section 7.1.7). Ovalling is counteracted and local stability maintained creating the potential for decrease in chimney shell construction material volume.

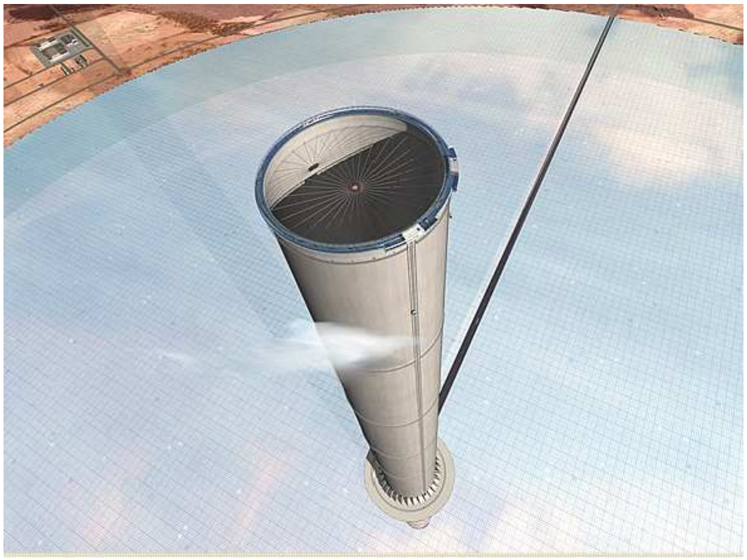


Figure 8-12. Spoked wheel concept visible at chimney tip [Schlaich Bergermann und Partner 2004].

<u>Spanning cables concept</u>

The circumference of a concrete shell may be stiffened by several cables spanning diagonally across the through-flow section of the chimney in a repetitive pattern [Glubrecht 1973], see figure 8-13. The concept mitigates circumferential shell buckling with consequent cost reduction due to decreased wall thickness. Research on this concept using 36 steel cables placed in triangular fashion proved to be the most efficient in increasing buckling stability [Lourens 2005].

Research at the US-ISE aimed to compare various circumferential stiffening concepts to identify the most optimal. The spanning cables concept proved to be the most stable when subjected to linear elastic buckling analyses.

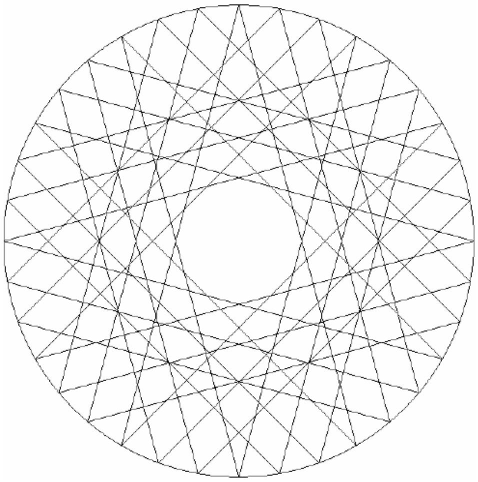


Figure 8-13. Spanning cables concept [Glubrecht 1973].

Concluding on circumferential stiffener trend

The requirement of low solidity contradicts the requirement of stiffness. In its history the circumferential stiffener concept only achieved low solidity with low stiffness (e.g. cooling tower ring) or high solidity with high stiffness (e.g. bamboo), except for bicycle wheels, which are not a large scale reinforced concrete application. The only judgement that can be made about the performance of this stiffening concept in structures is based on numerical research. The investigation performed on circumferential stiffening rings indicates that the high stiffening–low solidity concepts are at the forefront of circumferential concrete shell stiffening technology. The requirement of low solidity contradicts the requirement of stiffness, a combination that has not yet been achieved in practice. This technology, classified as a new and emerging concept in circumferential stiffening, is awarded the emerging rank of 1.

### 8.3.7 Cable staying

Cable stays are difficult to isolate as a technological entity since it always serves as an element in a larger system; the interaction between the cables and other structural systems is pronounced [Walther et al. 2003]. The main parameters/features making these elements successful as structural members are therefore studied and their history and furtherance discussed in the context of their implementation in cable-stayed structures, for example long-span bridges and guyed masts.

Stay cables of as long as 500 meters in span displaying low natural frequencies, such as 0.2 or 0.3 Hz in the lowest mode [Fujino 2002], have been used. Furthermore, because of their low inherent damping (as low as 0.1% critical damping ratio), they often respond adversely (resonance) due to rain- and wind-induced action. Cable vibration controls include connecting wires and passive dampers (installed near the cable anchorage), roughness increase and deployment of controlled dampers [Fujino 2002].

High tensile strength steel wire ropes and strands, typically with tensile strength of 1,500 MPa, density of 7,850 kg/m$^3$ and modulus of elasticity of around 200 GPa, are commonly used in cable stays. Increase in the material strength–weight ratio over the past decades enabled a substantial increase in the capacity of cable elements to resist loads, for example by utilising light weight carbon reinforced plastic fibers [Krishna 2001] and other composites. The density of carbon fiber-epoxy is typically 1,600 kg/m$^3$ (significantly less than that of steel) with modulus of elasticity of 145 GPa and a tensile strength ranging from 234 MPa to 3,300 MPa [Callister 1997].

Cable stays are often very exposed structural elements and must be protected against aggressive corrosive environments [Walther et al. 2003]. Enhanced corrosion resistance of metals, as well as development of high strength non-metallic materials which are inert to the effect of corrosion, efficiently mitigate corrosion based failure [Krishna 2001]. The high costs of non-metallic materials presumably limit their incorporation in standard cable designs.

Most of the challenges experienced with cables and cable systems seem to be understood and largely mitigated. Expected improvements are in material performance (weight, strength and durability) by incorporation of other advanced performance materials, the controlling of vibrations and in the innovative layout toward an efficient structure, remembering that the layout of cable stays is one of the fundamental items in the realisation of economically feasible structures influencing not only the structural performance, but also the method of erection [Walther et al. 2003].

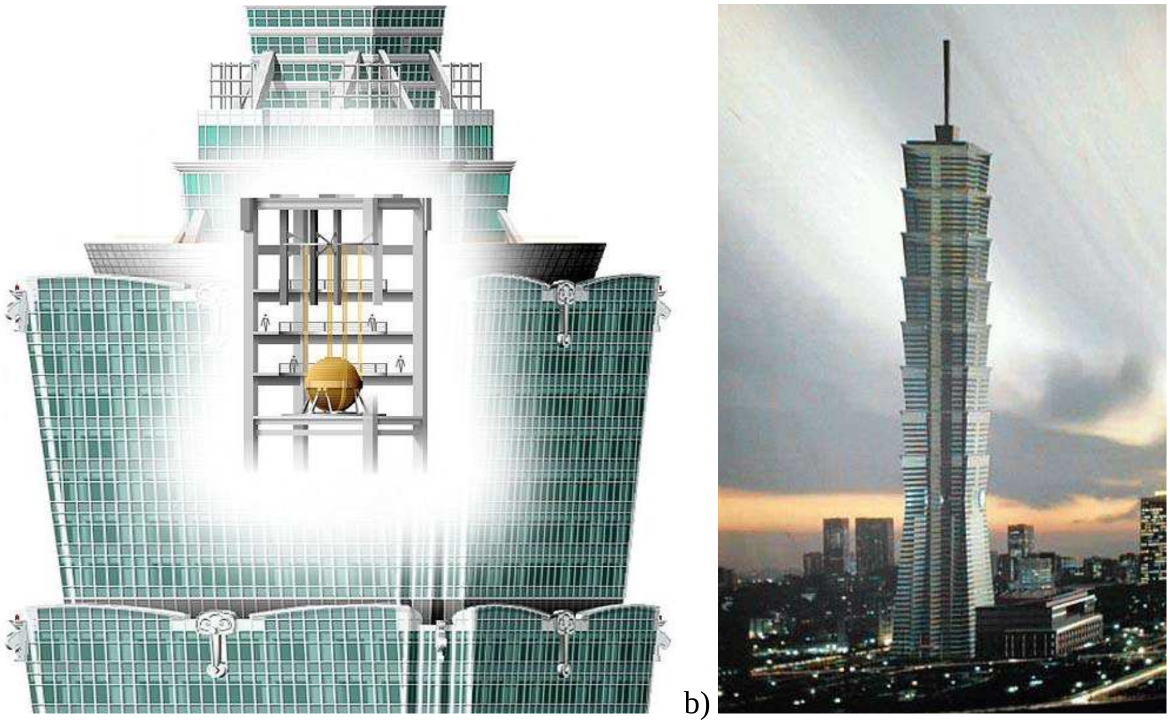
Although adequate damping can reportedly not be provided for extremely long stay cables, the emergence of semi-active dampers combined with material improvements may provide feasible solutions.

Cable stay technology is well established and implemented in a wide range of structures. Expected improvements lie with the vibration mitigation and the introduction of lighter, stronger materials combined with innovative layout solutions. Some challenges before its implementation on the SCPP chimney remains to be addressed, for example the extreme lengths of cable required to reach the preferred heights. Cable stay technology is awarded a growing rank of 2+ (negative curvature on Figure 8-1).

### 8.3.8 External damping

The damping in a system indicates its ability to dissipate vibration energy. Over the past three decades the reduction of structural response caused by dynamic effects has become a subject of intensive research [Datta 2003]. Structural designers increasingly make use of auxiliary damping devices. Figure 8-14a displays an example of a tuned mass damper as implemented in the upper region of the super tall Taipei 101 structure (Figure 8-14b). The 662 ton pendulum damper, situated at the 87th floor is suspended from the 91st floor and utilises active hydraulic cylinders to control the motion of a massive weight.

External dampers are classified as passive, active and semi-active control systems. In this section a qualitative investigation into the emergence and current status of these systems is performed.



a) b)

Figure 8-14. a) An example of a tuned mass damper [Internet 5 2008] as implemented in the b) super tall Taipei 101 building [Internet 6 2008].

## Definition of external damping systems

Passive control systems do not require an external power source for operation and utilise the motion of the structure to develop the control forces. Control forces are developed as a function of the response of the structure. Examples of passive dampers are base isolation devices, visco-elastic dampers, tuned mass dampers, liquid column dampers, orificing of fluid and friction dampers [Symans and Constantinou 1999].

Active control systems typically require a large power source for operation of electro-hydraulic or electro-mechanical actuators which supply control forces to the structure. These forces are developed based on feedback from sensors that measure the excitation and/or the response of the structure. Examples of active dampers are active tuned mass dampers, active tendon systems and actuators/controllers.

Semi-active control systems do not introduce mechanical energy into the structural system but rather manipulate system properties in an optimal manner to reduce the structural response [Yalla et al. 2001]. They typically require a small external power source for operation and utilise the motion of the structure to develop the control forces, the magnitude of which can be adjusted by the external power source. Control forces are also dependent on excitation and/or response feedback. Examples of semi-active dampers are electro-rheological, magneto-rheological and fluid-viscous and tuned mass dampers.

## Technology performance, emergence and maturity

A significant number of tall structures were realised with a variety of passive and active vibration control devices. Although it is not yet routine design practice to design external damping capacity into a structural system, it is becoming prevalent with the emergence of tall and super tall buildings. Mass dampers, in either passive, active or hybrid form, are the most frequently used devices with over 20 major installations in buildings and observation towers worldwide [Kwok and Samali 1995].

The major benefits brought about by the introduction of active control systems are the smaller damper mass and higher efficiency. While conventional mass dampers may provide an additional damping of 3% to 4% of critical damping, resulting in a 40% to 50% reduction in the wind-induced response, active systems can add an additional damping of 10% of critical damping with reduction in wind-induced response of up to 65% [Kwok 1995]. However, the control equipment required for an active system could increase its capital cost – a conventional tuned mass damper system could cost 1% and an active system 2% of the building cost. Active control systems are scrutinised due to the problems encountered in their practical implementation such as modeling errors and response delay [Datta 2003], paving the way for a new generation of damping systems: semi-active control.

Semi-active control systems have only recently emerged in structural control applications [Symans and Constantinou 1999]. The development and experimental testing of semi-active control systems for applications in structural response control has only been pursued approximately ten years ago. Therefore, many of these systems are immature and a comparison among various systems may not be as appropriate as it would be in a subject which had reached a more mature performance level.

Literature confirms performance increase with semi-active controls where, in general, the performance of the structure with the semi-active control system was superior to that of the structure with a passive control system, while simultaneously requiring smaller control forces. Furthermore, the development of control algorithms which explicitly incorporate the control system dynamics and control-structure interaction may produce further improvements in the control performance [Symans and Constantinou 1999].

Concluding on external damping technology trends

It is concluded that external damping systems are, with the emergence of semi-active control, evolving into more efficient, less expensive means of structural control. Semi-active controls – the new generation of structural response controls – may replace the bulky or expensive passive and active control systems. An in-depth investigation could provide more quantitative insight into the measure of performance increase and its applicability to the SCPP chimney. For the current decision-making process it is appropriate to consider this technology as *growing*, with much potential toward mitigating adverse action on the SCPP chimney; hence it is classified as early growth period and awarded a growing rank of 2– (positive curvature on Figure 8-1).

### 8.3.9 Directional wind design

Directional wind loads are caused by varying surface roughness of the surrounding terrain within a radius of 5 to 10 km and regional wind climatic effects representing the typical prevailing winds and paths of storms at the site. In directional design the orientation of a building is optimised to have the strong axis in the extreme wind direction and to have the weak axis in the direction of the weaker storms [Kasperski 2007]. Niemann et al. [2007] investigated the implications of directional wind on cooling tower design and noted that the directionality of wind loading on structures implies directionality of wind induced stresses. The complete spectrum of directional factors must be considered to avoid an over-conservative design, relinquishing the concept of rotational symmetry, taking advantage of load reduction and designing a reliable structure according to the directional variation of the wind loading.

For tall structures, such as the proposed SCPP chimney, the conditions in the upper air layers may further impact the directional design on the chimney. The “Ekman Spiral” describes the phenomenon where the wind direction and the impact of the Coriolis force on it decrease with increased surface frictional effect on the high-to-low pressure gradient vector. The Ekman Spiral effect causes the wind vector to turn gradually towards the low pressure centre as the ground surface is approached and can amount to a total angular change between gradient height and surface of about 30 degrees [Holmes 2001]. This phenomenon has to be characterised for the Sishen SCPP chimney.

Directional wind design technology application is relatively mature since it merely requires detail design applying the resulting directional response. In history this approach was used for structural optimisation, but not for detailed radial directional cost reduction in cylindrical structures. The aspects surrounding the occurrence of the Ekman Spiral effect and its influence on the directionality of the wind remain less characterised. This technology is awarded a growing rank of 2 (linear on Figure 8-1).

It is concluded from the trend investigation exercise that several technologies are emerging and growing:

- parabolic hyperboloid geometry,
- material elastic modulus,
- wind extrapolation,
- external damping and
- directional wind design

Others are mature and merely require standard implementation (wall thickness re-configuration).

### 8.3.10 Solar Chimney Power Plant chimney research at the University of Stellenbosch - ISE: Cascade of Technological Trends

The Cascade of Technological Trends presented in section 3.6.2 indicates a normative pattern for technological development. The US-ISE/BUW-SDT research efforts are measured against this norm. Their efforts covered the following:

- material characteristics, i.e. Cascade Level 1[ii]
- the structural operating principle and system size, i.e. Cascade Level 2
- structural performance, i.e. Cascade Level 3
- cost decrease and reliability, i.e. Cascade Level 4
- market (cost) dictated technology conceptualisation, i.e. Cascade Level 5

The chronology of these R&D events is displayed in Figure 8-15 (Appendix H, section H1, summarises the broader US SCPP research program over the past decade). The R&D was spread out over several cascade levels, mostly Levels 2 to 4. This may indicate the inability to decouple cascade levels in structural research or the definition of research topics without a governing, directing system and technology perspective, covering as wide a scope of subject matter as is tempting during radical innovation (in order to address all potential broad-based uncertainty). A RIM approach, with its systems and technology based perspective, could guide resource allocation for such radical innovations, moving from the lower, physical science cascade levels through to the higher, user satisfying levels. Figure 8-15 portrays a general chronological trend from Level 1 to Level 5 suggesting that R&D at the US-ISE is reaching a more mature phase when considering the current research priorities. This indicates a normal development toward technology maturity – with its market ready status (Level 5).

Further, investigation of the R&D topics treated at the US-ISE shows that cost aspects (a Level 4 cascade) were seldom considered.

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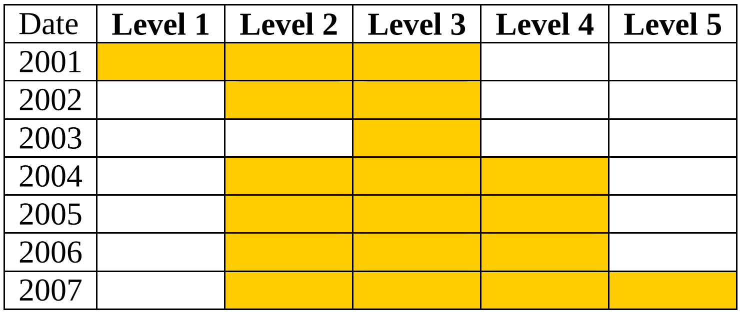
[ii] These “levels” are different from systems hierarchy levels treated in section 8.2.



| Date | **Level 1** | **Level 2** | **Level 3** | **Level 4** | **Level 5** |
|---|---|---|---|---|---|
| 2001 | 🟨 | 🟨 | 🟨 |  |  |
| 2002 |  | 🟨 | 🟨 |  |  |
| 2003 |  |  | 🟨 |  |  |
| 2004 |  | 🟨 | 🟨 | 🟨 |  |
| 2005 |  | 🟨 | 🟨 | 🟨 |  |
| 2006 |  | 🟨 | 🟨 | 🟨 |  |
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Figure 8-15. Involvement in cascade levels over the 7 year US-ISE research program.

## 8.4 Determination of research and development risk

With core technology trends identified the last step in the current RIM phase concerns the determination of R&D risk for the technologies. Various R&D risks are presented through semi-quantitative measures with values and definitions displayed in Table 8-4. Values are determined based on estimations of the effort required to develop the technology performance up to the level of augmented or technologically introduced performance proposed in Chapter 7 (Note that the author gathered these values based on personal exposure to this wide range of technologies. Resource allocation allowed only this personal impression; a more thorough forecasting exercise could provide more accurate data. Still, this procedure is efficient in illustrating the application of the RIM). The key to definition and value of R&D risk was presented in section 4.1.4 – a value of 1 indicates low R&D risk and 5 high R&D risk. The purpose of this study is *not* to address the capability of the US-ISE of contributing to the SCPP chimney technology development, but focuses on the risks of global technology R&D.

Four technologies require significant to very high R&D input:

- material elastic modulus,
- material damping,
- external damping and
- increased chimney height technology.

Several technologies exhibit moderate R&D risk while low R&D risks are indicated by

- the applicability of the critical buckling factor,
- inner surface friction,
- parabolic hyperboloid geometry,
- number of circumferential stiffeners and
- wall thickness re-configuration.

Table 8-4. Value allocation for R&D risk of system technologies.

| **Alternatives** | **R&D risk: (1=low; 5=high)** | **Comment** |
|---|---|---|
| Wind velocity extrapolation model | 3.0 | Extreme wind load cases in the SCPP must be differentiated. Thunderstorm turbulence is understood in theory and needs region specific characterisation. The applicability of dynamic response evaluation models must be verified. |
| Cross wind force spectrum | 3.0 | A moderate, focused R&D input could provide adequate characterisation of this field. |
| Flaring chimney exit geometry | 3.0 | High meridional stresses and susceptibility to buckling necessitates moderate R&D. |
| Concept of circumferential stiffeners | 3.5 | This emerging technology requires significant R&D toward optimisation and implementation. |
| Elastic modulus | 5.0 | A very high level of R&D resource commitment is required to increase concrete E-modulus without significant cost increase. |
| Concrete density | 3.5 | Light-weight concretes do exist but has to be high strength for the SCPP chimney requiring moderate to high level R&D. |
| Internal damping | 4.5 | A significant effort in material development could have the required impact on internal damping. |
| Cable stiffening | 3.5 | Basic technology is known but significant breakthroughs are needed toward implementation involving breakthrough material characteristics and cost, damping and layout. |
| Parabolic hyperboloid geometry | 2.0 | Basic technology is well known; it must be adapted for the SCPP. |
| Increased chimney diameter | 3.0 | High meridional stresses and susceptibility to buckling necessitates moderate R&D. |
| Number of circumferential stiffeners | 2.0 | Assuming that concept technology is proven, technology must be adapted for the SCPP. |
| Wall thickness reconfiguration | 1.0 | Technology must be implemented on the SCPP. |
| External damping devices | 4.5 | High to very high R&D input is required to bring this field of technology to its full potential and applicability to SCPP chimneys. |

| | | |
|---|---|---|
| Saguaro geometry with lower limit structural function | 3.5 | The concept is understood to a large degree. It has to be optimally adapted and implemented to the SCPP. |
| Directional design | 3.0 | After the characterisation of the Ekman Spiral for the relevant region, it requires only design application. |
| Increased chimney height | 4.0 | Dynamic susceptibility to buckling and dynamic excitation necessitates R&D breakthrough. |
| Terrain surface roughness | 3.0 | Obtainment of the required site could be a high risk endeavour. |

## 8.5 Conclusion

This chapter applies the tools proposed for technology characterisation, classification and trend identification phases of the RIM on the technologies that performed well or remains under characterised in the system performance evaluation. Uncertainties related to technologies that provide functionality at several levels of the system are characterised. The characterisation and classification present a framework from which technology acquisition may be managed by identifying technologies with similar characteristics from the technology landscape. The trend investigation disclosed several emerging and growing technologies (parabolic hyperboloid geometry, material elastic modulus, wind extrapolation, external damping and directional wind design) while others are mature and merely require standard implementation (wall thickness re-configuration). R&D risk was identified for each system technology yielding a perspective on the R&D input required to realise the augmented or introduced technologies.

This technology-based insight enables strategic decision-making – performed in the next chapter – not only on the basis of technology performance, but also with its maturity and consequent potential for improvement in mind.

# CHAPTER 9

# TECHNOLOGY STRATEGY

During incremental innovation strategic decisions are made with business sense based on insight into financial models, R&D risk models and short to medium terms time frames. Radical innovation decision-making utilises insight gained during the previous chapters, providing knowledge and insight into potential performance improvement of the system as well as into the potential of realising required technological performance levels.

The technology tree (Chapter 6, Section 6.4) provides a systems perspective on the technological function of the SCPP chimney system by breaking it down from chimney system level through foundation, chimney-to-foundation and chimney, with their respective sublevels, to the fourth level where the technological components are located. Opportunities and gaps in the system can readily be identified and placed in this comprehensive framework.

The system performance evaluation phase evaluated technologies in terms of criteria for the radical innovation, specified at strategic level. Five technologies emerged as superior on the grounds on their potential impact on system performance (Chapter 7, Section 7.4). These are:

- the parabolic hyperboloid geometry,
- wall thickness re-configuration,
- material elasticity modulus,
- the more accurate characterisation of the wind extrapolation model and
- the number of circumferential stiffeners.

The following technologies were identified for further investigation:

- cable stiffening,
- external damping and
- the directional wind based design.

Technology assessment (Chapter 8) provides a descriptive framework and classification of each identified technology in the SCPP chimney system, from which specific technology development or acquisition can be managed. Technology growth trends indicate the maturity and potential for improvement of individual technologies. The growth status of each technology was awarded a rank in Section 8.3. The determination of R&D risk and technology maturity for each technology (awarded in Section 8.4) provides information on risks of achieving augmented or introduced technological performance goals through R&D.

This chapter concludes the RIM proposed in this thesis by the formulation of a strategy roadmap for the SCPP chimney radical innovation using the systems and technology insight gained during preceding phases of the RIM application. Frameworks for understanding the radicality and uncertainty of the radical innovation and technological impact on these uncertainties combine with knowledge of the potential for, and probability of, technological improvement and integrate into a knowledge basis for strategising a radical innovation roadmap. The R&D facilities of the company are consequently tasked with technology development, stating priorities and re-allocating resources, directing in-house development of system technological capabilities and potential while, externally, driving interaction or acquisition in response to technological opportunities or threats.

Strategy is formulated with aid from the Technology Position Analysis. The consummation of the RIM takes place with the Technology Position Analysis. The set up of system hierarchy and technology identification, the tedious process of model choice and set up, implementation of technology contribution for evaluation, the technology assessment and trend identification all contribute information to the Technology Position Analysis. A rightfully comprehensive judgement can be performed, incorporating not only the system performance evaluation and technology trend projections, but also the risk of the technology of reaching the sought performance level. The Technology Position Analysis further provides efficient communication of technological information and strategy through its active visualisation of results.

## 9.1 Visualisation of results

With all the information gained from previous RIM phases, R&D strategy can now be set up. A Technology Position Analysis (refer to section 3.7) places all chimney system technologies in perspective – one sheet presenting technological information to aid strategic decision-making.

### 9.1.1 Information fields

Several information fields can be efficiently portrayed in a Technology Position Analysis. In the current analysis the potential performance gain (from Chapter 7), R&D risk (from section 8.4) and technological maturity (from section 8.3) fields are depicted. These measures adhere to the criteria deemed important for radical innovation as stated in Table 2-1 – determining technological benefits in terms of market requirements – by incorporating SCPP chimney technology performance potential, while R&D risk indicates the level of input and effort required to achieve the stated performance level. Technology maturity indicates on the same sheet the maturity of the chimney technologies.

The criteria of performance improvement must depict the performance measure that is most representative of the technology (for example, in the SCPP chimney, the structural performance metrics would be LEC, buckling or dynamic response).

The maturity of the technology provides a quantitative/qualitative impression of the amount of improvement expected from the technology in future. An emerging technology, for example, holds much potential for impacting the system (although uncertain to what extent) as it is developed into a mature, relevant technology. Only SCPP chimney technologies that display positive impact on system performance were assessed in terms of maturity; the others are lower priority and are not considered. Technological maturity rankings were determined in section 8.4.

### 9.1.2 Results from Technological Position Analysis

The current application of the Technological Position Analysis is briefly discussed; data is placed on the position map with the system performance metric on the Y-axis and R&D risk on the X-axis. A high-performance, low risk technology is the most favourable with technologies becoming less favourable moving to the low performance, high risk region – Figure 9-1 illustrates. The technologies that participated in trend assessment are depicted in the figures further in this section, by circle-markers with their size indicating the maturity of the technology. Technologies that did not undergo trend assessment are represented by triangular markers. Some technology values were offset slightly in order to facilitate visualisation. Note that although R&D risk of the technological improvements may differ for different criteria, this study assumes the values from Table 8-4 to be applicable to all criteria. Upper and lower limits, as well as uncertainty, although not quantified, are depicted by error bars. The under-characterised technologies are also portrayed here.

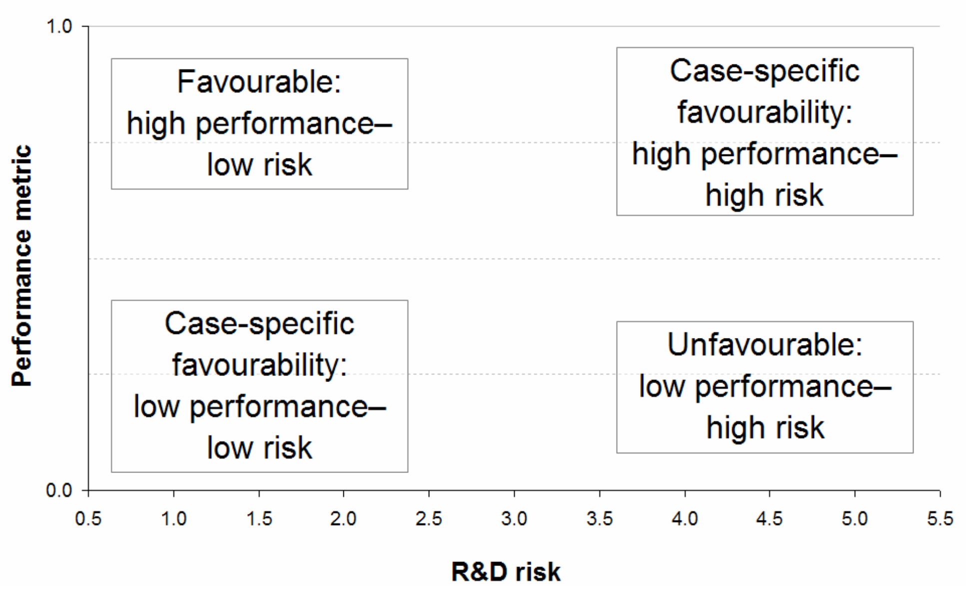

Figure 9-1. Qualitative portrayal of quadrants in the Technological Position Map.

Results: LEC metric

The technologies responding most favourably in the LEC Technological Position Analysis are the following – refer to Figure 9-2:

- Parabolic hyperboloid geometry is the most favourable displaying high performance at relatively low R&D risk. Its growing technology trend indicates potential for improving its performance.
- Wall thickness re-configuration technology performs moderately, but at low R&D risk.
- The number of circumferential stiffeners performs below par on this metric (bear in mind its major impact on the buckling metric), but is relatively low R&D risk.
- The increased chimney height (and its coupled technology – the cross wind force spectrum) performs well in terms of LEC, but at moderate to significant R&D risk levels.

Flaring chimney geometry yields moderate performance at moderate R&D risk. Most other technologies do not perform significantly in this metric (or is currently only described in terms of upper or lower limit and uncertainty), with moderate to high associated R&D risk. An exception is the high risk, poorly performing material elasticity modulus technology.

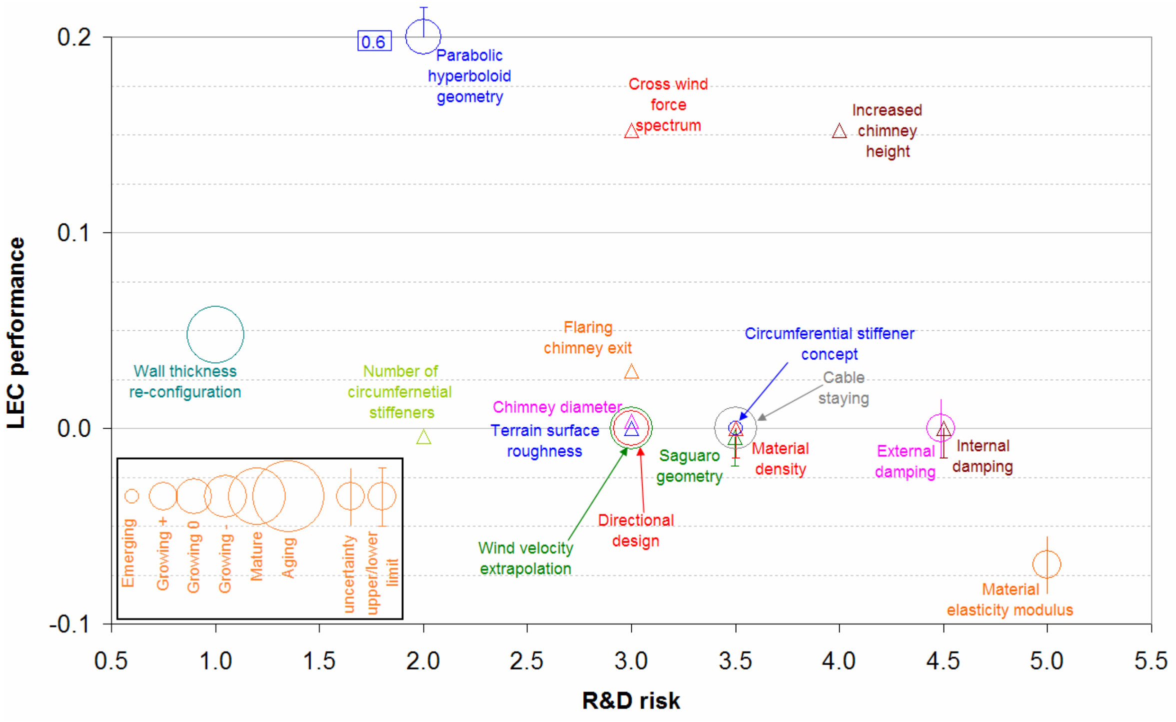

Figure 9-2. Technological Position Map for displaying LEC performance against R&D risk.

## Results: buckling metric

The technologies responding most favourably in the buckling Technological Position Analysis are the following – refer to Figure 9-3:

- The wall thickness re-configuration performs very well at very low R&D risk; it is mature and does not promise much technological breakthrough – its implementation as is yields significant results.
- The number of circumferential stiffeners performs well at low R&D risk.
- Wind velocity extrapolation is a growing technology that performs well and at moderate R&D risk.
- Terrain surface roughness performs moderately at moderate risk.
- The Saguaro geometry performs moderately at moderate to significant R&D risk.
- Material elasticity is a growing, high R&D risk technology that promises high performance impact.

Several other technologies do not perform significantly in this metric with moderate to significant associated R&D risk, with the exception of the increased chimney diameter, flaring chimney exit and circumferential stiffener concept that perform poor and at moderate R&D risks.

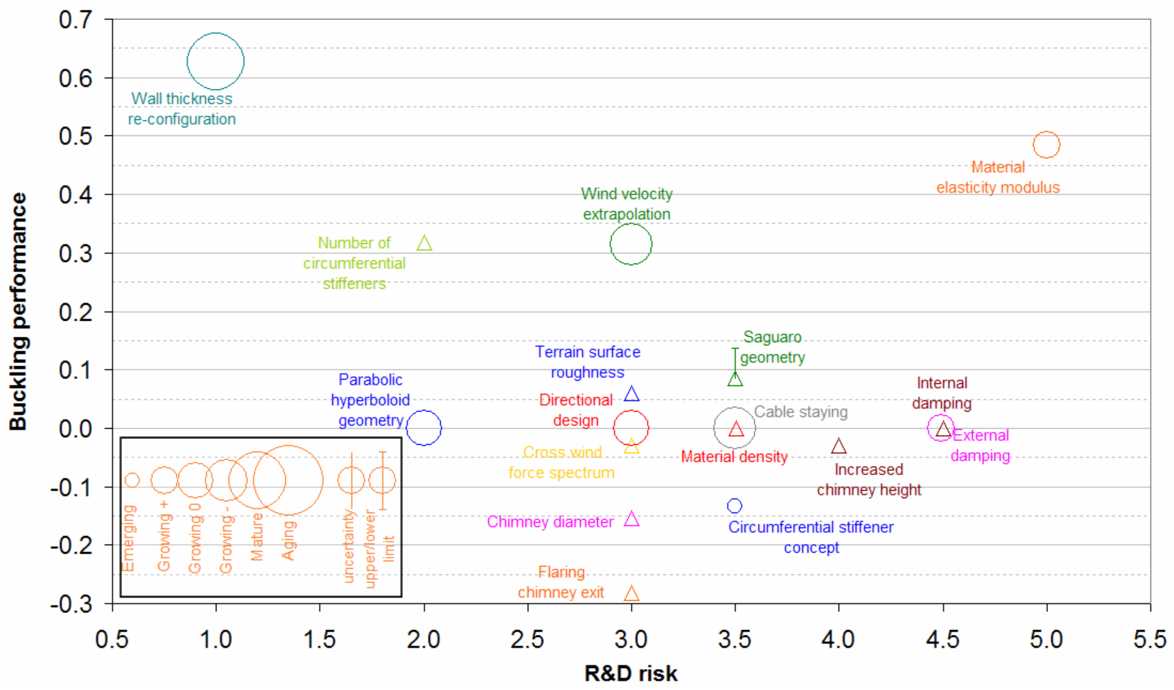

Figure 9-3. Technological Position Map for displaying buckling performance against R&D risk.

Results: dynamic response metric

The technologies responding most favourably in the dynamic response Technological Position Analysis are the following – refer to Figure 9-4:

- The chimney diameter, wind velocity extrapolation and terrain surface roughness technologies perform excellently in this metric and at moderate R&D risk.
- Wind velocity extrapolation is a growing technology.
- Material density and the Saguaro geometry perform moderately at moderate to significant R&D risk.
- Material elasticity modulus performs excellently, but at very high R&D risk.
- Internal damping performs moderate to well at high R&D risk.

Several technologies perform very poorly due to lock-in behaviour. These are wall thickness configuration, increased chimney heights and its coupled cross-wind force spectrum and also the parabolic hyperboloid geometry.

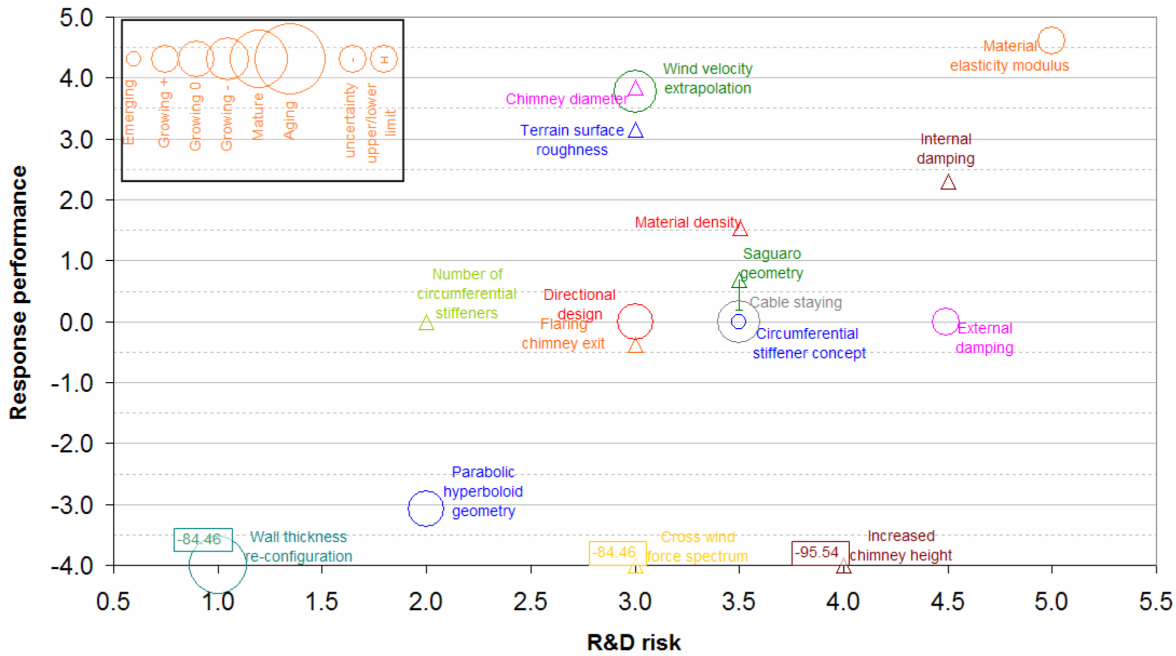

Figure 9-4. Technological Position Map for displaying dynamic response performance against R&D risk.

### 9.1.3 Discussion on Technology Position Analysis

The system performance evaluation pointed out the system performance gain potentially brought about by each technology implementation or addition. It did not incorporate the R&D risks associated with realising the augmented or technologically introduced performance levels – a metric that is crucial toward efficient strategising. The Technology Position Analysis provides all the SCPP chimney technologies with performance gain, technology risk and maturity in one comprehensive view. The maps must be updated iteratively as information following R&D effort is gained and incorporated in the system.

Currently the technologies are spread over a wide range of performance and R&D risk values, because the SCPP chimney radical innovation requires broad scoped conceptual investigation. The map space is also filled with technologies with negligible contribution; subsequent iterations must clear out the space with only the contributing technologies remaining, bearing in mind which technologies were left out to retain a systems perspective on the chimney. The higher risk SCPP chimney technologies may not be feasible even with sufficiently allocated resources, but the decision-maker now knows the impact and risks of technologies in the system. R&D can be re-directed to more promising (lower R&D risk) technology developments and breakthroughs (probable high R&D risk with potentially high performance returns) for efficient acquisition and incorporation into the user system – a higher risk technology must promise significant performance potential before it becomes feasible to pursue it as R&D priority.

Note that a thoroughly implemented MCDM approach would compact the maps that were set up for the decoupled criteria into one comprehensive map. This coupling of results to give a comprehensive view on favourability, may simplify the strategy formulation.

The next section presents the SCPP chimney R&D roadmap by stating development priorities that are apparent with all the system and technological insight gained through the RIM.

## 9.2 Technological development priorities

This section summarises the R&D priorities as they became evident through technology assessment, Technology Position Analysis based priorities (technology performance gain, R&D risk and maturity) and other insight.

### 9.2.1 Technology assessment based priorities

Characterisation observations

The technology Framework of Basic Features and Nine Cell Technology Functional Classification Matrix provide definition to each technology from which improvements may be identified and other similar technologies identified for acquisition. The technology management academic fraternity is working toward comprehensive technology taxonomy to facilitate identification of similar technologies [Van Wyk 2004]. Hopefully this will soon become a reality.

Some general observations can be made concerning the characteristics of the technologies in the SCPP chimney:

- Several technologies concern the characterisation of action effects. These are thunderstorm turbulence characterisation, directional design, cross wind force spectrum (directly) and terrain surface roughness and temperature characterisation (indirectly).

- Several technologies concern the stabilisation of the chimney under buckling. These are parabolic hyperboloid geometry, wall thickness re-configuration, circumferential stiffeners, cable staying, external damping devices, internal damping, Saguaro geometry and circumferential stiffener concept and number.
- Several technologies focus on increasing the energy yield. These are diameter increase, flaring exit geometry and increasing height.
- Several technologies concern the improvisation or alteration of the reference case material, i.e. reinforced concrete. These are material density, elasticity modulus and internal damping.
- Only the directional design approaches *specifically* addresses cost issues. This may be due to the stage of development of the SCPP chimney where structural realisation is the main concern toward system realisation. As the concept converges to structural feasibility, the focus must be redirected toward LEC optimisation. Structural criteria will then not be specifically quantified, but only represented in the cost criterion, as is typical in standardised design practice.

### Technology classification observations

The Nine Cell Technology Functional Classification Matrix provides a comprehensive (although robust, at this stage in its development) definition to each technology from which improvements and other similar technologies may be identified. It was determined that the SCPP chimney fulfils the function of *processing* and *transporting* load-based energy, while *transporting* air-matter from the collector centre to the mid tropospheric regions. Damping systems temporarily *store energy*.

### TRIZ problem solutions

Although the TRIZ methodology was not distinctly implemented in this investigation, literature promises it to be a powerful identifier of solutions to contradictions. These solutions could direct the radical innovation process toward typical solutions.

Tendency of priority technologies

In terms of the above sets of characteristics observed in the chimney technologies, the technologies identified to hold priority portray the following:

- The three top rated priority technologies are primarily concerned with stabilisation of the structure.
- Two high performance but low R&D risk technologies – the parabolic hyperboloid geometry and wall thickness re-configuration – were only implemented in the SCPP chimney model at a late stage during its development. This shows that high potential technologies can be overlooked and provides merit for the application of a systems approach to conceptual and radical innovation.

Cascade of Technological Trends

The technology trend cascade observations (section 8.3.10) identify that few technologies aim at decreasing cost directly. Only one technology specifically addresses cost, while the top three priority technologies mainly concern structural stabilisation, a Level 2/3 cascade.

### 9.2.2 Technology Position Analysis based priorities

The technologies are ranked to provide an order of importance for a R&D program. Table 9-1 provides the ranked R&D topics and motivates their rank.

### 9.2.3 Other insights and priorities

Stay in touch with other concepts and potential solutions

As stated in section 5.2.2, several varying concepts are proposed as a solution to the highest level SCPP chimney function, i.e. sustaining a through-flow channel. Even when research avenues are already decided and committed to, alternatives need to be kept in mind as to whether they provide more optimal solutions to the problem than the currently investigated one, i.e. keep the feelers “out there”, continuously on the lookout for promising solutions. Research managers must stay open-minded, following the TRIZ approach of lateral problem solving with performance as close to the IFR as possible, even if this entails a complete change in research direction and thinking.

Table 9-1. Research priorities based on Technology Position Analysis.

| Rank | R&D topic | Motivation |
|---|---|---|
| 1 | Incorporation of wall thickness re-configuration and investigation for mitigating adverse dynamic response. | Very significant mitigation of buckling with moderate reduction of LEC at very low R&D risk. |
| 2 | Incorporation of parabolic hyperboloid geometry and investigation for mitigating adverse dynamic response. | Very significant LEC reduction at low R&D risk. |
| 3 | Incorporation of more circumferential stiffeners, given the concept is proven. | Moderate mitigation of buckling at low R&D risk. |
| 4 | Wind velocity extrapolation profile characterisation, decreasing uncertainty in wind action model. | Moderate impact on buckling mitigation at moderate R&D risk. |
| 5 | Investigation to region's surface roughness characteristics in the area of the proposed site of construction. | Low to moderate impact on buckling mitigation at moderate R&D risk. |
| 6 | Investigation of mitigating adverse structural behaviour in increased chimney height. | Significant impact on LEC reduction at high R&D risk. |
| 7 | Investigation of mitigating adverse structural behaviour in flaring chimney. | Low to moderate impact on LEC reduction at moderate R&D risk. |
| 8 | Remain in touch with developments/breakthroughs in cable staying, external damping and directional design technology. | Further introductory/ familiarising investigations may prove productive toward identifying this field as a potential priority area. |
| 9 | Remain in touch with developments/breakthroughs in concrete material characteristics. | Although very high risk R&D, significant breakthroughs may impact significantly on structural integrity. |
| 10 | Further investigation to realise Saguaro geometry in order to mitigate adverse dynamic response. | Low to moderate impact on buckling (lower limit) at moderate to high R&D risk. |

The fact that solutions and improvements may come from unforeseen directions (brought about by the multi-disciplinary and broad-based technology scan and foresight exercises) should be acknowledged, necessitating caution to not, on the basis of previous experience or conventional methods, write off an idea.

Look to nature for solutions

In spite of the “incredible” scientific ability of humans, nature often still provides the most simple and efficient solutions. Krishna states that “nature often indicates new solutions – the falling of a tree across a rivulet may have triggered the field of bridge engineering … and the spider’s web may have spurred on the ideas of tension nets or membranes” [Krishna 2001]. The comprehensive perspective on the SCPP chimney set up in this research reveals that several reference and proposed solutions are nature based solutions:

- Parabolic hyperboloid base geometry copies the typical base geometry of trees with a gradual broader tapering at the lower levels.
- Circumferential stiffeners are found in bamboo trees that portray exceptional slenderness ratios.
- Saguaro cacti ribs mitigate detrimental wind pressure fluctuation and suction peaks.
- Directional design had always been applied in plants with their root growth stimulated in areas of greatest stress occurrence. Trees, however, all start with one seed, without statistical insight into the extreme actions it will experience in its lifetime – it has measures to adapt intelligently.

On the grounds of these potentially successful technologies the study of nature for similar structures must form a part of the future strategy for SCPP chimney R&D.

The first iteration of the RIM on the SCPP chimney is thus concluded with the successful formulation of the SCPP chimney R&D strategy. As more information and insight is acquired and knowledge is gained, the models and first iteration reference RIM framework can be updated, refining the decision-making. The validation of the RIM is, however, completed in a single iteration having performed all the distinct RIM phases up to a point of efficiently formulating R&D strategy.

## 9.3 Concluding the Radical Innovation Methodology application

The RIM was applied on the case of the radical innovation of the SCPP chimney concept to systematise radical innovation for well founded R&D strategy formulation, thereby supporting the thesis of this dissertation. The chapters of Part II yield significant insight through a systems and technological approach on the problem of feasibility of the SCPP chimney. The systematic RIM approach yields frameworks for the efficient identification and management of uncertainties in the SCPP chimney system, and of R&D priorities for development to a state closer to chimney feasibility. Where previous R&D management was based on intuitive and specialist identification of R&D priorities, the systems approach followed in the RIM provides a comprehensive, non-intuitive view of the chimney system – all current and subsequent R&D can be sorted in the drawn up systems hierarchy and technological frameworks. Specific and general priorities are identified in a clear SCPP chimney R&D strategy. Note: this dissertation concludes with an epilogue[i] that reports results of the synthesis of four of the technologies identified to be top priority for incorporation into a second iteration reference case. The re-evaluation of this improved chimney concept yields results that are *significantly* closer to sought performance levels.

### 9.3.1 Specific priorities

Results from the system performance evaluation combine with technology trend identification and R&D risk values to provide Technological Position Maps for comparing technologies. These maps and previous findings from the RIM application provide insight to a comprehensive understanding of technological capability and potential. Priority technologies were identified: wall thickness re-configuration, parabolic hyperboloid geometry and increased number of circumferential stiffeners (given the concept is proven) must be incorporated in the system with the necessary R&D allocation to bring these technologies to their augmented or technologically introduced states. More investigation must focus on the characterisation of the wind velocity extrapolation profile and manipulation of the region's surface roughness. Mitigation of adverse dynamic response on the wall thickness re-configuration, parabolic hyperboloid geometry, increased chimney height and flaring chimney geometry must be sought. Technology managers must remain in

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[i] The results reported in the epilogue, although very significant for SCPP chimney R&D, are not directly applicable to the development of the subject thesis; hence it is not reported in the main text. The reader is invited to view these interesting results.

touch with developments and breakthroughs in cable staying technology, external damping and material elasticity modulus; their high R&D risks imply a (presumably) greater effort than what in-house commitment could deliver. The structural impact of the Saguaro cactus geometry must be investigated more thoroughly.

### 9.3.2 General priorities

Several tendencies in the SCPP technological portfolio are identified that indicate previously successful R&D: research managers should remain open-minded and on the look out for similar and interesting technologies/concepts for further investigation, introduction and augmentation; problem solving ideas must not be written off without proper consideration; nature must be engaged in search of technological solutions; and the structural R&D must soon engage the technology differentiating research as specified in the Cascade of Technological Trends.

This concludes the first iteration of the RIM with the formulation of research strategy. The uncertain, fuzzy nature of radical innovation was systematised through the RIM, delivering a methodology for formulating R&D strategy through systems and technological perspectives on the radical problem.

# CHAPTER 10

# CONCLUSION

This chapter concludes the dissertation with a summary of the thesis argument *and* its resolution. Recommendations for further research on the thesis topic are made.

## 10.1 Summary of background and motivation and the thesis statement

The incremental innovation process can dramatically improve the performance of a system by novel implementation of codified design practice through interpretation and manipulation from scientific first principles. Radical innovation is required, however, in the *absence* of codified practice at one or more lower levels in the system. It requires innovation *outside* the familiar realms of standardised, formalised theory and practice by identifying, re-interpreting and addressing the basic system functionality that requires solution.

Radical innovation is characterised by high degrees of multi-disciplinary technical, market, resource and organisational uncertainty and unpredictability. Its time frames are long with sporadic project terminations and revivals, nonlinear recycling of the response to previous setbacks and stochastic change of priorities and champions. Radical innovation aims to progressively reduce uncertainties in radical concepts through their sufficient characterisation to attract further investment. This cannot be provided by mere parameterised design or relevant organisational support as is sufficient for incremental research; the lack of understanding of the radical innovation process causes executives to make *normative* strategy decisions based on mainstream business. A more comprehensive approach is required to understand the complexities and uncertainties of the radical innovation. The need for a systematic, methodological approach to managing – delimiting and characterising – uncertainties in radical innovation is evident. The thesis statement was formulated: *radical innovation can be systematised through the synthesis of existing theory to form a basis for strategic decision-making.*

A major motivation for this study arises from the demand for sustainable solutions, cultivating a long-term perspective in an attitude of custodianship after the many negative impacts that the rise of technological enterprise in the 20th century had on the social, economical and ecological environment. Engineering perspective must broaden to view technologies as socio-technical systems that are responsive to the broader environment. This process may require radical technological intervention demanding the fast-tracking of radical technological solutions for solving of some critical global crises.

The 1,500 meter tall chimney structure of the SCPP fits as a case study for implementation of the RIM. Radical challenges and uncertainties must be resolved toward its structural and economic realisation and its positive impact on the global climate change crisis. The methodology developed for this thesis responds to the specific demand for the set up of an innovation strategy for development of the SCPP chimney structure up to feasibility.

## 10.2 Resolution of the thesis

### 10.2.1 Part I: synthesis of the Radical Innovation Methodology

The first part of the thesis synthesised the RIM. The fragmented, indeterminate (with regard to *radical* innovation) tools of incremental innovation management currently used for managing the erratic, uncertain characteristics of radical innovation were systematised and extended through MOT theory. Part I investigated two scientific fields, SE and MOT, for their potential contribution to the synthesis of a systematic approach aiding a RIM. SE, by its comprehensive nature, provides valuable insight into the system functionalities and a systematic, non-intuitive framework within which uncertainties and deficiencies can be identified, characterised and delimited. The technology perspective brought about by MOT unlocks insight into the building blocks of the radical innovation by the characterisation and delimiting of technological status, potential and uncertainty.

SE and MOT theories were synthesised into a generic systematic radical innovation methodology, the RIM. The RIM furthers SE, managing high uncertainty in user systems due to perpetuated lower level uncertainty found in radical innovation. This is achieved through extending high level system performance measurement and strategy formulation to incorporate quantitative low level technological R&D and evaluation through the technology assessing and evaluating approach of MOT methods. The systems approach provides a framework for characterisation of the radical innovation, while MOT characterises and determines maturity and growth trends of the technological sub-systems that form user systems, enabling reasoned decision-making at an executive level.

The RIM is formulated in five distinct phases. A reference case is set up in response to board specified requirements and broken down to its functional, technological elements moving outside the constraints of standardised design practice and its limit state equations; this is achieved through engaging the functional realm of technology. Each technology is augmented or newly introduced in the system context and evaluated to determine its potential for furthering system performance. Its technological characteristics and maturity as well as the R&D risk of realising the sought technological performance are determined. During the last phase strategy is formulated based on the systems and technological insight gained.

The integrated roles of a technology manager, technological expert and board were identified for the RIM: the technology manager facilitates and compiles the RIM process with supportive roles from the experts (technology specific insight) and the board (strategy specific insight).

### 10.2.2 Part II: validation of the Radical Innovation Methodology

The proposed RIM was applied to the SCPP chimney structure radical innovation in the second part of the document. It illustrated the value of the RIM through providing a systematised approach toward SCPP chimney R&D strategy formulation. A reference case was set up in response to a demand for a 1,500 meter tall chimney. The radicality of the reference case was determined to provide an understanding of the measure of functional performance improvement needed. The chimney was broken down into its technological elements. Each technology was augmented or introduced to determine its potential impact on system performance in terms of board and expert specified criteria – several technologies emerged as critical for significant improvement in system performance. These technologies were assessed and their maturity and R&D risk determined to contribute to a comprehensive, pro-active perspective on the SCPP chimney technologies status and potential for impact.

<u>Critical technologies identified</u>

Technologies that emerged as critical are:

- the wall thickness re-configuration,
- the incorporation of parabolic hyperboloid geometry and

- the incorporation of more circumferential stiffeners.

These technologies promise very high to moderate impact on system performance at very low to low R&D risk.

Three technologies promise to mitigate adverse dynamic response at moderate impact on other criteria, and at moderate R&D risk. These are:

- the more thorough characterisation of the wind extrapolation profile,
- the potential manipulation of the region's surface roughness character and
- the incorporation of the Saguaro cactus geometry.

The mitigation of adverse dynamic response could open up possibilities for increasing the chimney height, while buckling mitigation could open possibilities for the flaring of the chimney exit geometry. The cable staying, external damping and directional design as well as developments and breakthroughs in concrete material technology, especially its elasticity modulus, must be monitored or further investigated because their improvement holds promise for SCPP chimney system performance improvement.

Technology characterisation and further observations pointed out that significant further characterisation of action effects on the chimney needs to be performed and that only one technology focuses on the reduction of SCPP system LEC. Technologies were classified in the Nine Cell Technology Functional Classification Matrix for future reference. Overall future R&D on the SCPP chimney should stay in touch with other concepts and similar technologies as well as focus on solutions presented by nature.

The application of a systematic approach to SCPP chimney radical innovation revealed two low R&D risk technologies (wall thickness re-configuration and parabolic hyperboloid geometry) that promise significant impact on the system performance. These critical developments were only considered at a late stage of the chimney innovation due to the non-structured approach to radical innovation.

<u>General R&D considerations proposed</u>

The following general R&D considerations are identified or proposed:

- Research managers should remain open-minded and on the look out for similar and interesting technologies/concepts for acquisition,
- Problem solving ideas must not be written off without proper consideration,
- Nature must be engaged in search of technological solutions and

- The structural R&D must soon engage the technology differentiating research as specified in the Cascade of Technological Trends

### 10.2.3 The value of a Radical Innovation Methodology

The thesis presents a systematic approach streamlining and fast-tracking the non-empirical, non-intuitive process of radical innovation, thus saving and optimising time and other R&D resources. Opportunities that could have previously been overlooked are now systematically identified. Uncertainties are distinguished and delimited in a comprehensive framework from where they are characterised for focused functional mitigation.

A *radical* innovation methodology is presented where previously only incremental innovation management procedures were available. The fields of SE and MOT are extended by exploiting their contribution to the RIM synthesis. The successful first iteration application of the RIM on the SCPP chimney supports the significant contribution of this systematic approach to engage the uncertainties and unknowns characteristic of radical innovation.

The RIM presents a *generic* approach to the solution of radical innovations; the systems approach and characterisation of functional elements of the system are generic to any problem. A sought-after solution is broken down from its main R&D theme to its essential functionalities from where uncertainties and gaps can be characterised and delimited for efficient R&D management. For example, the alleviation of the global HIV/AIDS endemic (radical action and breakthrough is required) may be broken down to the awareness toward abstinence from HIV/AIDS transmission, physical HIV/AIDS extermination through breakthrough medical technology, temporary health care, etc. The impact of each element may be determined by virtually augmenting its ‘performance’ and its priority for achieving sought system performance evaluated. In the case of the absence of required functionalities new technologies may be introduced. Thus, comprehensive perspective of the system and its critical facets is available before prioritising resources for further investment.

## 10.3 Recommendations and suggestions

### 10.3.1 General Radical Innovation Methodology recommendations

The RIM presented in this dissertation mainly concerned radical technological innovation for a system with functionalities as required during the operational phase in its life cycle. Further research on the RIM may expand and customise it to be applicable to every phase of the system life cycle, with incorporation of the various criteria that are important at various life cycle phases. Also, specific implications of the progression from radical to incremental innovation on the formulation of the RIM should be investigated and described.

The RIM focused mainly on the technological uncertainties of radical innovation. Further investigations could provide organisational, logistical and resource support for this methodology. The systematic procedure could enable a more logical derivation of organisational and logistical support. Also, their (and the market's) uncertainties could be managed through the principles presented by the RIM.

SE and MOT are fields covering wide scopes from overall systems perspectives to detailed methodologies and tools with steps for exact application. Broader and more detailed investigation of their premises and specifics may add to the RIM synthesised in this dissertation. Furthermore, the SE and MOT fields are relatively young scientific fields in which theoretical and practical developments are still expected; the expansion and extension of its theory, for example the detailed classification of technology in a taxonomical framework, may enable the more thorough classification of system technologies and increase the insight gained into their character and dynamics for more focused R&D strategy.

The RIM, being defined as a generic methodology, could be customised for numerous other radical innovations. The functional, problem-solving perspective on innovations takes a step back to identify the system of which the problem forms a part. Gaps and uncertainties are delimited and functions required for addressing these gaps are qualified. The impact of ideal or perfect performance improvement of the uncertainty is evaluated to identify critical elements in the system. These can be characterised, classified and assessed in terms of the potential for realising the sought improvement. Consequently, strategy is formulated to address the re-allocation of resources to address the critical functionalities.

### 10.3.2 Solar Chimney Power Plant recommendations

Only the first iteration of the application of the RIM on the SCPP chimney was performed. Subsequent iterations must narrow down and characterise the concept and its uncertainties. Accompanying R&D may identify other or further R&D focus areas. The radical innovation should eventually become sufficiently characterised to be further manageable by standardised design procedures.

Several issues were not addressed due to resource constraints, amongst others the constructability of the SCPP. Future research should focus on investigating these issues to fill in the missing pieces in the comprehensive framework of the SCPP chimney system.

Investigation into accurate, representative MCDM methods could better inform the SCPP chimney decision-making process.

The emergence of the other SCPP chimney concepts may prove to be more feasible than the reinforced concrete chimney chosen in this dissertation as reference case for the RIM application.

The systematic approach presented by the synthesis of SE and MOT approaches in the Radical Innovation Methodology streamlines radical innovation and formulation of its R&D strategy. It presents a systems based framework from which critical technological elements and uncertainties are identified and characterised and growth trends and R&D risks are identified, thus enabling reasoned decision-making. The Radical Innovation Methodology holds a key to the resolution of radical, critical challenges mankind is faced with in the 21st century.

# EPILOGUE

In a step that is preparatory to a second iteration reference case formulation, four of the top technologies (section 9.2.2) are incorporated into the first iteration reference case:

- The wall thickness re-configuration, as formulated in section 7.1.13, is included in combination with
- the parabolic hyperboloid geometry (section 7.1.10),
- the addition of the five additional circumferential stiffeners (section 7.1.12) and
- the ultra-high strength performance concrete (section 7.1.8) (a modulus of elasticity at 60 GPa was chosen in the latter case).

Note that the other technological subjects are not incorporated into the system yet due to resource constraints. Further, note that not all these synthesised technologies are developed up to the value that they are introduced or augmented at in this synthesis.

The synthesised system yields excellent results (summarised in Appendix I). The energy yield has a slightly lower limit than that of the parabolic hyperboloid system of section 7.1.10 due to the presence of the additional circumferential stiffeners, at 304.13 GWh/y, which is approximately 0.3% lower than that of the reference case. The capital costs are reduced from R27.70Bn to R8.55Bn resulting in a LEC of R3.63/kWh (This significant decrease in capital cost is mainly due to the exclusion of the fins stiffening structures. The fin-stiffened chimney system contained almost three and a half times the concrete required by the parabolic hyperboloid geometry chimney system.). The critical buckling factor surpassed the 'ideal' 5.0 mark with a first global buckling mode value of $\lambda_1$ = 5.75. The first global free vibration frequency is at 0.113 Hz resulting in a gust load factor, which is almost 4% above that of the reference case, but safely outside any critical wind velocities.

The new, synthesised LEC value is lower than with any individual technology augmentation. The structural performance against buckling is significantly better, having surpassed the barrier stated as the ideal result, while the gust load factor does not pose any significant threat. It is concluded that the implemented systematic RIM approach proposed by this thesis, resulted in significant cost and structural benefits, thus leading the SCPP chimney development several steps closer to structural and economical realisation.

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# APPENDIX A

# FINITE ELEMENT ANALYSES

The Finite Element Method model and analyses procedures for the Chimney are presented here. DIANA Finite Element Analysis version 9.2 FE software [DIANA 2007] is used throughout.

## A1 FEM model

### A1.1 Mesh

A finite element (FE) model generated and calibrated in previous research [Rousseau 2005] forms the basis for the model used in this investigation (see Figure A1 – left and middle). Eight node quadrilateral iso-parametric curved shell elements, CQ40S, are used to model all structural shell elements (chimney and longitudinal fin stiffening structures); three translational and two in-plane rotational degrees of freedom are available per node. Two node Bernoulli beam elements, L12BE, are used to portray the columns supporting the chimney; three translational and three rotational degrees of freedom are available per node. Additional lateral stiffening beams are deployed between adjacent fins to model the constraint effect that the collector roof has on the fins to prevent buckling. The model is simplified by modeling only half the chimney. This assumption is made due to geometrical and loading symmetry about the axis of wind direction. Note that this approach assumes loading and response symmetry, for instance not capturing torsional action and response.

### A1.2 Constraints

Due to the symmetry simplification of the model the nodes on the symmetry axis are constrained appropriately. The stiffeners are not modeled directly, but their effect is included by the constriction of rotation around the vertical axes at the proposed locations of stiffening (Figure A1 – right). Note that the circumferential stiffener “spokes” are displayed only and did play an active structural role.

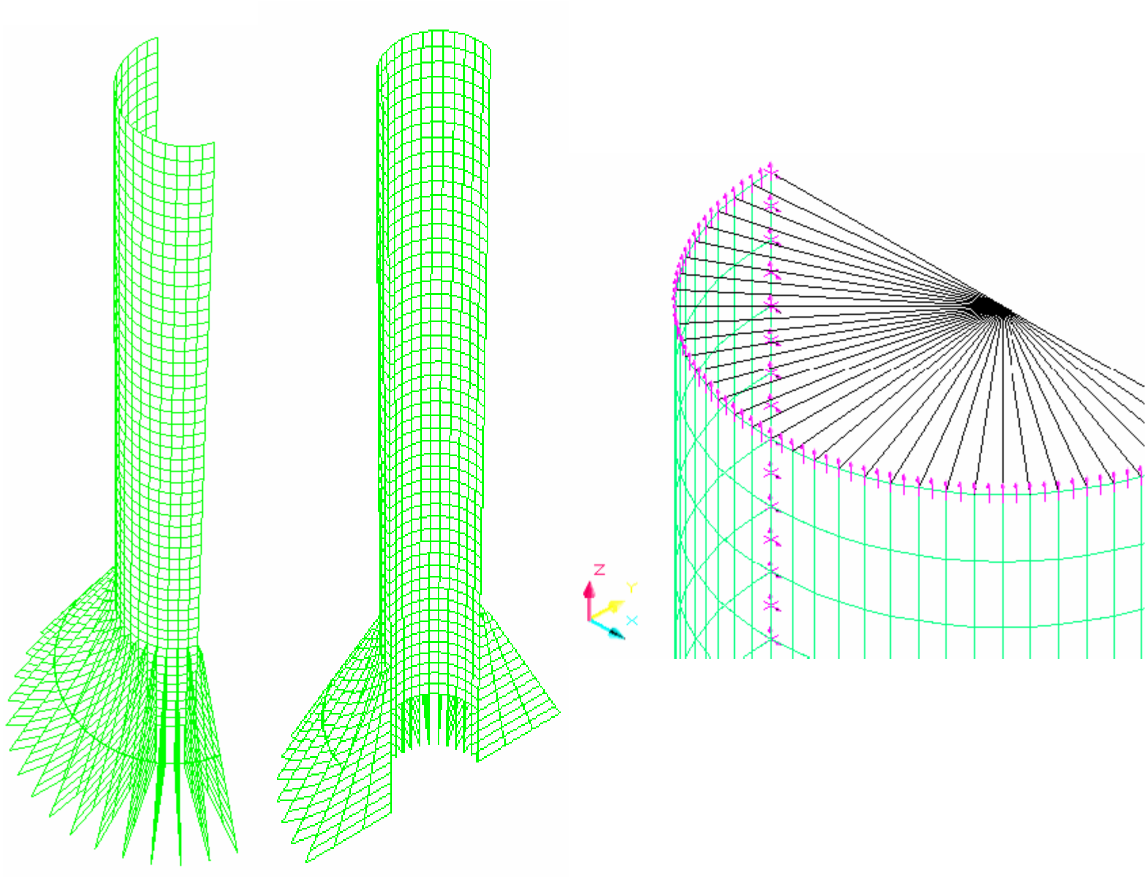

Figure A-1. The FE model (left and middle). The rotational constraint about the global z-axis (right).

The impact of the Sishen soil/rock characteristics on structural performance is evaluated in the FEM model. Soil/rock characteristics are introduced to the model with a spring model prescribed by Gazetas [1983]. The soil/rock characteristics are subdivided in the following horizontal layers in Table A-1:

Table A-1. Soil/rock characteristics for the Sishen region.

| | | **Soil/rock characteristics** | |
|---|---|---|---|
| **Layer** | **Depth [m]** | **Elasticity modulus [average GPa]** | **Poisson ratio [average]** |
| Top layer: Kalahari sand | Between 0 and 0.8 | n/a; excavated | |
| Limestone | Between 0 and 50 | 10.9 | 0.26 [Hart and Wang 1995] |
| Weathered lava rock | Between 20 and below | 66.9 | 0.26 |

Soil deformation assumes linear isotropic visco-elastic behaviour [Gazetas 1983]. Soil stiffness characteristics of the actual soil system can be replaced by a bed of independent elastic springs resting on a rigid base. On the basis of field measurements, tables and empirical formulae were presented from which one can readily estimate design values of the coefficient for several types of soil for all possible modes of vibration. The following frequency-independent coefficients apply to response in the low frequency range:

$$K_v = \frac{4GR}{1-\upsilon} \tag{A1}$$

where $K_v$ = spring constant (stiffness) [N.m]

$R$ = radius of the circular rigid loading area [m]

$G$ = shear modulus [Pa]

$= \dfrac{E}{2(1+\upsilon)}$

$E$ = elasticity modulus of soil [Pa]

$\upsilon$ = Poisson's ratio of soil

The expressions for the four degrees of freedom and the corresponding values for limestone and weathered lava rock assuming a foundation size of 240 meter radius (160 meter chimney diameter plus two 160 meter fin stiffener structures) follow in Table A-2. The foundation is assumed to be a circular disk below the chimney and fin stiffeners.

Table A-2. Equivalent spring stiffness values for rock substrate.

| **Mode** | **Vertical** | **Horizontal** | **Rocking** | **Torsion** |
|---|---|---|---|---|
| **Stiffness formulation** | $\frac{4GR}{1-\upsilon}$ | $\frac{8GR}{2-\upsilon}$ | $\frac{8GR^3}{3(1-\upsilon)}$ | $\frac{16GR^3}{3}$ |
| **Limestone** | 5.61e+12 | 4.77e+12 | 2.15e+17 | 3.19e+17 |
| **Weathered lava rock** | 3.44e+13 | 2.93e+13 | 1.32e+18 | 1.96e+18 |

Each node on the base level of the FE model is awarded these translational and rotational stiffnesses. Subjected to the reference case wind loads the soil/rock show negligible change in the first global natural vibration frequency with it decreasing from 0.1943 Hz to 0.1942 Hz.

In conclusion (of the base fixity investigation) the SCPP reference case FEM model is constrained against all translation and rotation after determining that change in first global natural vibration mode, *with* base spring stiffnesses based on data from soil properties at Sishen being negligible.

### A1.3 Material and physical properties

The shell is made up of high performance reinforced concrete with an elasticity modulus of 30 GPa and Poisson ratio of 0.2. The elasticity modulus remains 30 GPa as only uncracked linear elastic buckling analyses are performed. The tube shell is partitioned in 51 horizontal sections to accommodate for the variation in wall thickness in a step-wise manner, assigning to each section the relevant thickness. The column beams are assigned a circular geometry of a constant 10.7 meter diameter.

## A2 Analyses

Linear elastic buckling analyses, free vibration analyses and frequency response analyses are introduced here – refer to section 5.3.1. The applicability of the frequency response analysis to the SCPP chimney response is discussed.

### A2.1 Linear elastic buckling

The linear elastic buckling analysis solves the following eigen-problem [for more detailed on buckling analyses refer to Bathe 1995]

$$(K_{L0} + \lambda_{crit} \cdot K_G)\delta U = 0 \qquad \text{(A2)}$$

where $K_{L0}$ = linear stiffness matrix

$\lambda_{crit}$ = critical buckling factor, i.e. factor on load in order to satisfy Equation A2

$K_G$ = geometrical stress stiffness matrix

$\delta U$ = displacement matrix

### A2.2 Free vibration

The free vibration analysis solves the eigen-problem

$$\left(K_{L0} + \omega^2 \cdot M\right)\phi = 0 \tag{A3}$$

where ω = eigen-frequency, or free vibration frequency, in radians per second

M = mass matrix

$\phi$ = eigen-vector, depicting the mode shape of the vibration mode

The free vibration analysis yields mode shapes that are excited at the corresponding frequency. The free vibration result in itself is not conclusive to determine structural integrity. The structural response to dynamic excitation determines its structural integrity. If its free vibration frequencies are excited during periodic loading conditions, it could lead to excitation of resonant oscillation, which could have detrimental effects on the structure.

### A2.3 Frequency response

The frequencies of typical wind load excitation spectra are concentrated in the lower frequencies and normally only endanger slender structures with global free vibration frequencies around the same spectrum. The structural response to the second global free vibration mode is generally considered negligible relative to the significant response of the first mode; this is confirmed in a frequency response analysis in DIANA FE software where a Davenport frequency spectrum [Rousseau 2005] is deployed to vary the *maximum* load on the SCPP chimney (Figure A-2). The figure displays peaks due to resonance at the first (0.135 Hz), second (0.225 Hz) and third (0.28 Hz) global free vibration frequencies but the latter two are significantly less than the peak at the first free vibration frequency, and than the static deformation (at 0 Hz). Note that the applicability of this analysis is limited because the frequency spectrum is a function of height, which DIANA cannot incorporate, and because the maximum peak wind load was varied while in reality it is only the gust that fluctuates around the mean wind load. It does illustrate a conservative case – the second free vibration mode will not be excited if larger than 0.2 Hz.

The conclusion is reached that only the first free vibration frequency and associated mode-shape need to be considered during dynamic analysis provided the second global free vibration frequency is larger than 0.2 Hz – this qualification must be verified for each technology alternative.

The simplified dynamic response calculation depicted from the Australian Wind Loading Code [AS1170-2:1989] is used in order to determine the quasi-static loading factor that is evaluated henceforth.

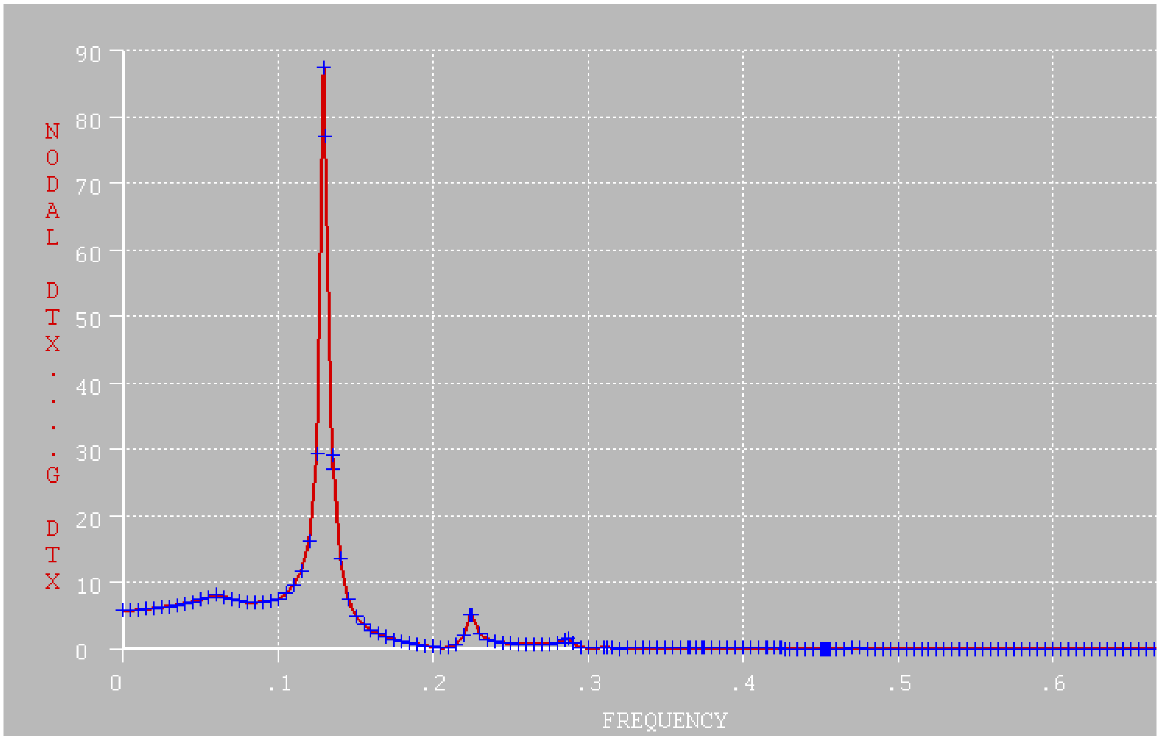

Figure A-2. SCPP chimney typical frequency response: amplified deformation of a windward node at the chimney tip.

## References

DIANA finite element analysis, Release 9.2 (2007), TNO DIANA.

Gazetas, G. (1983), *Analysis of machine foundation vibrations: state of the art*, Soil dynamics and earthquake engineering, Vol.2, No.1, CML Publications.

Hart, D.J. and Wang, H.F. (1995), *Laboratory measurements of a complete set of poroelastic moduli for Berea sandstone and Indiana limestone*, Journal of Geophysical Research, Volume 100, Issue B9, 17741-1752.

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# APPENDIX B

# WIND MODEL USED ON SCPP CHIMNEY

## B1 Reference wind load on SCPP chimney

Wind pressure loads on a structure surface are formulated as follows:

$$F_{z,\theta} = [C_{pe,\theta} - C_{pi}] \cdot q_{max,z} \cdot A \qquad \text{(B1)}$$

where $q_{max,z}$ = maximum expected gust velocity pressure [Pa]

$= ½\rho_z \hat{U}_z^2$ (B2)

$\rho_z$ = air density at relevant height [kg/m$^3$]

$\hat{U}_z$ = Expected peak gust velocity at height $z$ [m/s]

$= \overline{U}_z + g\sigma_{u,z}$ [Holmes 2001] (B3)

$\overline{U}_z$ = mean design wind velocity at height $z$ [m/s], as described by the corrected logarithmic profile [Harris and Deaves 1978]

$$= \frac{u_*}{k}\left[\ln\frac{z}{z_0} + 5.75\frac{z}{\delta} - 1.875\left(\frac{z}{\delta}\right)^2 - \frac{4}{3}\left(\frac{z}{\delta}\right)^3 + \frac{1}{4}\left(\frac{z}{\delta}\right)^4\right] \qquad \text{(B4)}$$

$\overline{U}_{10}$ = $U_{\text{design hourly mean, 10 meter height}}$

$= 1/1.53 \cdot U_{\text{design max 3 second gust, 10meter height}}$ [ISO DIS 2008]

$= 1/1.53 \cdot k_r \cdot U_{\text{max 3 second gust, 10meter height, 50yr}}$

$k_r$ = factor for adjusting for wind return period

= 1.17 for adjusting from 50 to 1,000 year return period; 1,000 years is chosen from the ISO code [ISO DIS 2008]. Note that a 2,000 year return period is used for reference case frequency response calculations.

$z_0$ = roughness length [m]

$z$ = height above ground level [m]

$\delta$ = height at which surface frictional effects are negligible, also known as the *gradient height* [m]

$$= \frac{u_*}{6 f_c} \tag{B5}$$

$u_*$ = frictional velocity [m/s]

$$= \sqrt{\overline{U}_{10}^{\,2} \cdot \kappa} \tag{B6}$$

$\kappa$ = surface drag coefficient

$$= \left[ \frac{k}{\ln\left(\frac{10}{z_0}\right)} \right]^2 \tag{B7}$$

$k$ = Von Karman constant

$\approx 0.4$

$f_c$ = Coriolis parameter

$= 2\Omega \sin \lambda$

$\Omega$ = earth rotational velocity [rad/s]

$= 7.27 * 10^{-5}$

$\lambda$ = latitude

$g$ = statistical peak value

$\sigma_{u,z}$ = standard deviation of wind velocity $\overline{U}_z$ on height *z*

$$= \overline{U}_z I_u \tag{B8}$$

$I_u$ = turbulence intensity

$$= \frac{1}{\ln\left(\frac{z}{z_0}\right)} \tag{B9}$$

$C_{pe,\theta}$ = external pressure coefficient, experimental results from SCPP research are used in this evaluation

$C_{pi}$ = internal pressure coefficient, experimental results from SCPP research are used in this evaluation

$A$ = surface area on which pressure is exerted [$m^2$]

With the formulation explained, the values can be calculated to determine the forces acting on the chimney. Table B-1 provides a logical layout of these calculations:

Table B-1. Calculations for wind forces on SCPP chimney.

| **Attribute** | **Value** | **Reference** |
|---|---|---|
| $U_{\text{max 3 second gust, 10meter height, 50yr}}$ | 40 m/s | SABS 0160:1989 |
| Return period used to factor load on SCPP chimney | 1,000 years | ISO DIS 2007 |
| Factor to correct 50 year to 1000 year wind velocity | 1.17 | SABS 0160:1989 |
| $U_{\text{design max 3 second gust, 10meter height}}$ | 46.8 m/s | |
| Factor to change from 3 second gust to hourly mean | 1.53 | ISO DIS 2007 |
| $U_{\text{design hourly mean, 10 meter height}}$ | 30.59 m/s | |
| Roughness length, $z_0$ | 0.02 m | Holmes 2001, Niemann 2007 |
| Von Karman constant, k | 0.4 | Dyrbye and Hansen 1997 |
| Surface drag coefficient, κ<br>$\kappa = \left[ \frac{k}{\ln\left(\frac{10}{z_0}\right)} \right]^2$ (B10) | 0.00414 | Holmes 2001 |
| Frictional velocity, $u_*$ | 1.969 m/s | Holmes 2001 |

| | | |
|---|---|---|
| $\kappa = \frac{u_*^2}{\overline{U}_{10}^2}$ (B11) | | |
| Sishen latitude, $\lambda$ | ≈ $28^{o}$<br>South | |
| Coriolis parameter, $f_c$<br>$f_c = 2\Omega \sin\lambda$ with $\Omega$ = earth rotational velocity = $7.27*10^{-5}$ rad/s | 6.826e-05 | Dyrbye and Hansen 1997 |
| Gradient height, $z_g$<br>$z_g = \frac{u_*}{6 f_c}$ (B12) | 4,807 m | Dyrbye and Hansen 1997 |
| Air density: $p = p_0 \left[1 + \frac{L \cdot h}{T_0}\right]^{\frac{gM}{-RL}}$;<br>where h = height above sea level; for Sishen: h = z + 1200<br>$p_0$ = sea level standard atmospheric pressure = 101325 Pa<br>$T_0$ = sea level standard temperature = 288.15 K<br>$L$ = temperature lapse rate = −0.0065 K/m<br>$R$ = universal gas constant = 8.31447 J/(mol·K)<br>$M$ = molecular weight of dry air = 0.0289644 kg/mol<br>$g$ = gravitational acceleration<br>$\rho = \frac{pM}{RT}$ with $T=T_0+L.h$ ; for Sishen h = z + 1200<br>Free stream velocity pressure<br>$q_{max,z}=½\rho_z \widehat{U}_z^2$ (B13)<br>The loads over chimney height are shown in Figure B-1. | | |

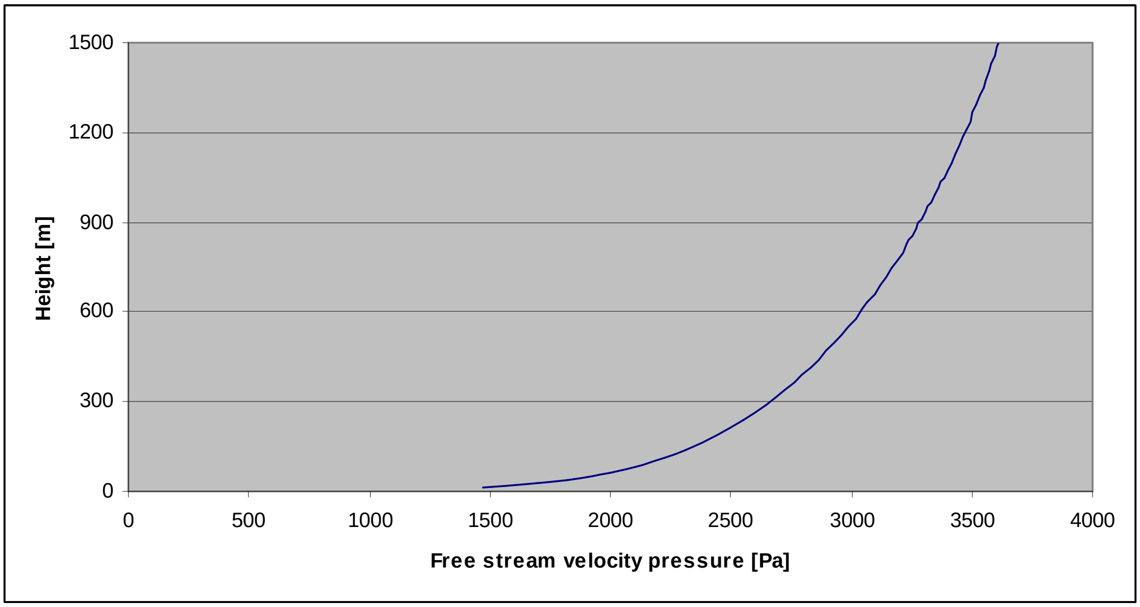


Figure B-1. Free stream velocity pressure increase with height.

Circumferential pressure coefficient

$$C_p = C_{p,\text{external}} - C_{p,\text{ internal}} \qquad \text{(B14)}$$

Two cases are investigated, one with maximum internal vertical flow, the other with no internal flow [Harte and Van Zijl 2007]. In both cases the 1.2D curve (see Figure B-2) is used due to its lower suction forces. The case with vertical flow ($C_{p,\text{ internal}}$ = -0.1 – see Figure B-3) is used further in this study on the grounds of its extreme peak at almost $C_p$ = -3, large negative wake pressures and larger pressure gradient. The resultant pressure coefficient distribution is shown by the blue curve in Figure B-4 (Note that the net pressure coefficients are portrayed – external pressure *and* internal suction pressure; hence the pink line value of 1.8 (unity pressure plus 0.8 internal suction) at zero degrees.). Finite element analyses of the SCPP under these two pressure distributions confirm greater global deformation and moment gradients.

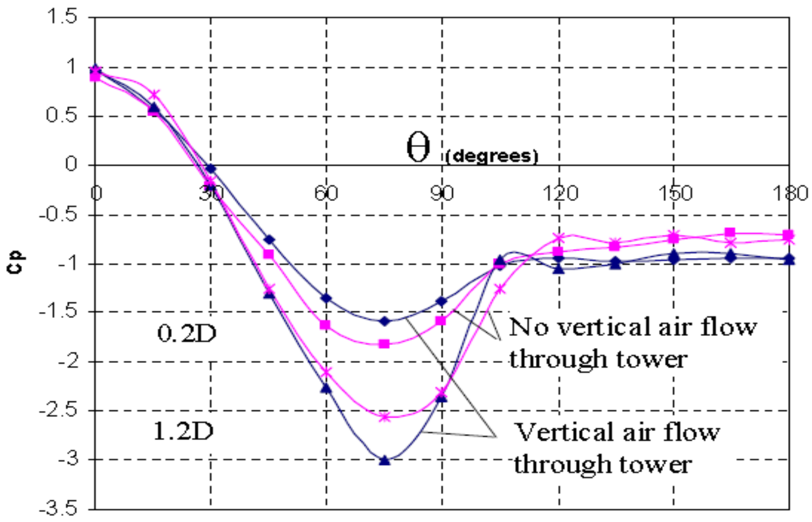


Figure B-2. External wind pressures at various positions along the circumference [Alberti 2006].

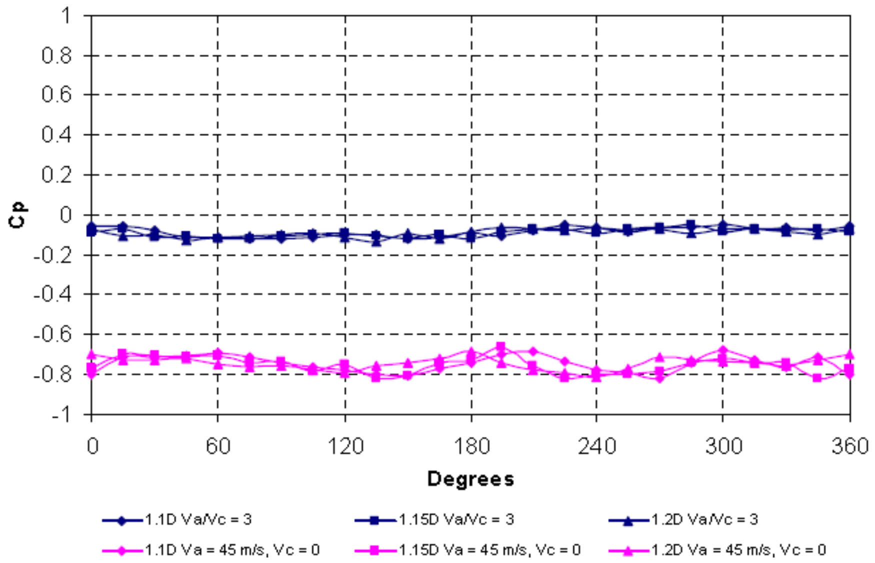


Figure B-3. Internal wind pressures at various positions along circumference [Alberti 2006].

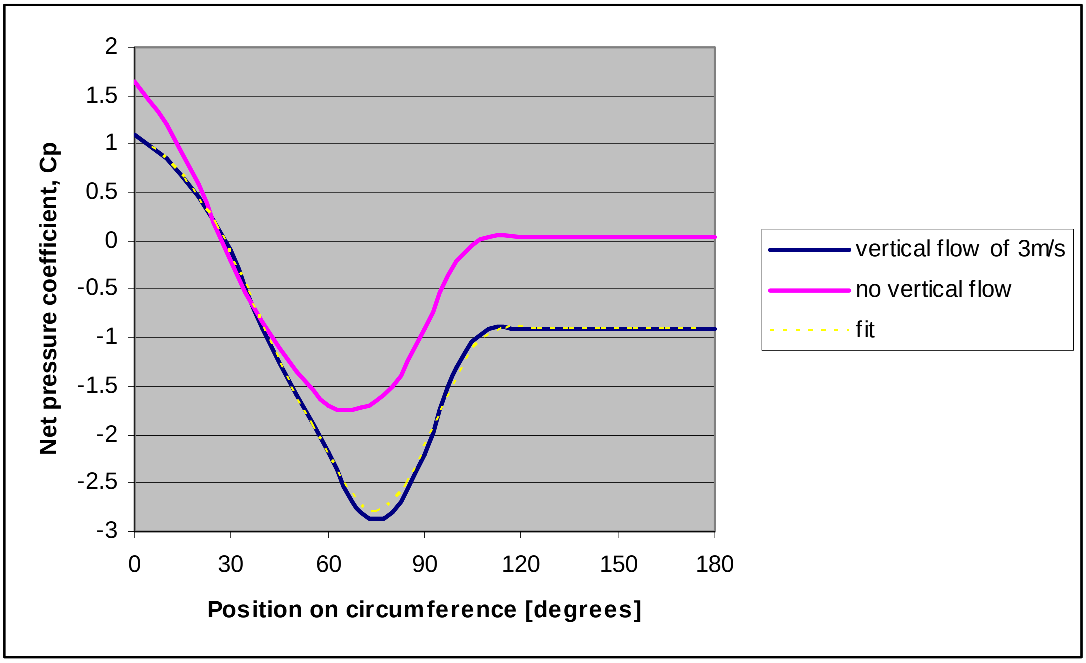


Figure B-4. Net wind pressures at various positions along the circumference

## References

Dyrbye, C. and Hansen, S.O. (1997), *Wind loads on structures*, John Wiley & Sons.

Harris, R.I. and Deaves, D.M. (1978), *The structure of strong winds*, Wind engineering in the eighties: proceedings of the CIRIA Conference on 12-13 November 1980.

# APPENDIX C

# STRUCTURAL PERFORMANCE EVALUATION MODEL

Structural performance evaluation in this dissertation, being a radical innovation that only aims to describe governing phenomena in order to formulate conceptual designs for means of evaluation, is measured by buckling and quasi-static dynamic amplification factors. These factors are compared to determine the impact of technological alternatives on the system performance.

## C1 Buckling

### C1.1 Analysis

Resistance of the SCPP chimney to global buckling serves as an indication of the impact on structural performance. The German cooling tower design guide [VGB 2005] prescribes the evaluation of buckling behaviour through a *linear elastic buckling analysis* under dead load and peak external and internal wind load (G + $W_{e,max}$ + $W_i$). Appendix A describes the mathematical formulation of this analysis for the numerical, FEM procedure.

### C1.2 Design limits and applicability thereof on the SCPP chimney

The German design guide prescribes the resulting first mode buckling factor to be *larger than 5* to allow for stress stiffnesses due to initial displacement. It accounts for nonlinear geometrical and material effects, determined empirically for cooling tower structures. The applicability of this factor to the SCPP chimney needs to be investigated in future.

Note that although resolution of this theoretical uncertainty does not improve the actual structural performance of the chimney, it provides a structural performance requirement metric against which structural performance of alternatives can be measured.

The wind load associated with the buckling analysis is formulated in Appendix B.

## C2 Quasi-static dynamic amplification factor

Appendix A reports the investigation into SCPP chimney frequency response. Only the first global free vibration frequency and associated mode-shape need consideration during dynamic analysis provided the second global natural vibration frequency is larger than 0.2 Hz. An analytical dynamic response calculation that is applicable to structures where only the first global vibration frequency is relevant, depicted from the Australian Wind Loading Code [AS1170-2:1989], is used in order to determine a quasi-static loading factor, based on along and across wind load factors.

### C2.1 Excitation due to along wind frequency spectrum

The along wind load factor, known as the *gust factor*, is a simplified parameter incorporating background and resonant response including simple structural geometry and dynamic behaviour, dynamic wind characteristics and the aerodynamic admittance and mechanical transmittance of wind to the structure. The background response is the slowly varying component of the fluctuating response caused by lower frequency wind speed variations while the resonant response accounts for the excitation of the natural frequency of the structure. This load factor (Equation C2) is applied on the mean base overturning moment caused by the quasi static mean wind action to determine the design peak base overturning moment

$$\hat{M}_a = G\overline{M}_a \tag{C1}$$

where $\hat{M}_a$ = design peak base overturning moment

$\overline{M}_a$ = mean base overturning moment resulting from the mean wind condition

$= \int C_D \overline{q}_z A_z dz$ ; with (C2)

$C_D$ = drag coefficient for cross section, chosen in accordance with Figure C-1

$A_z$ = area of a structure at height $z$

$\overline{q}_z$ = defined in Appendix B, equation B13, based on a 2,000 year wind

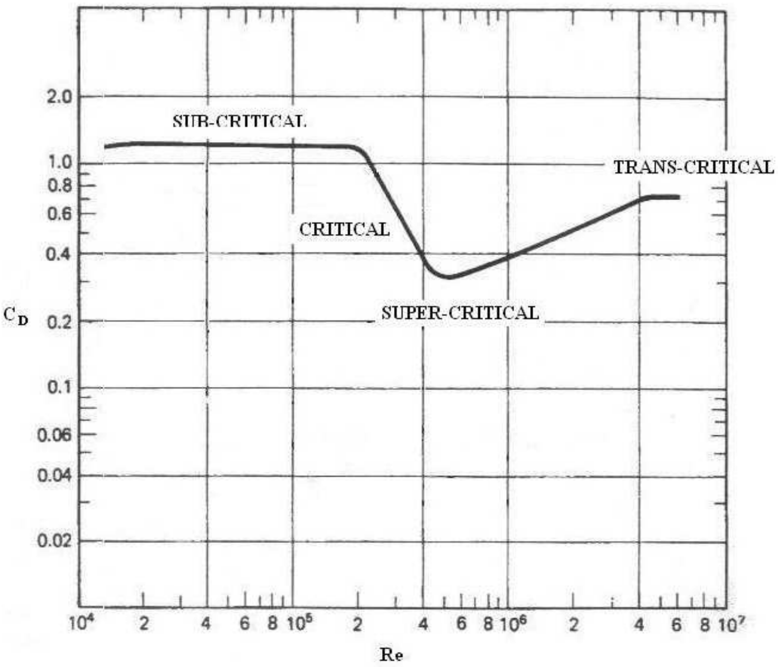


Figure C-1. Drag coefficient response to increasing Reynolds numbers.

G = gust factor

$$= 1 + r\sqrt{g_v^2 B(1+w)^2 + \frac{g_f^2 SE}{\varsigma}} \qquad \text{(C3)}$$

where r = roughness factor and

$= 2 \times I_u$ (C4)

$I_u$ = longitudinal turbulence intensity at height *h*

$$= \frac{1}{\ln\left(\frac{h}{z_0}\right)}$$

h = height of the building in meters

$z_0$ = surface roughness length in meters

$g_v$ = peak factor for upwind velocity fluctuation (gust)

= 3.7

B = background response factor

$$= \frac{1}{1 + \frac{\sqrt{36h^2 + 64b^2}}{L_h}} \qquad \text{(C5)}$$

b = horizontal breadth of the vertical structure normal to the wind direction

$L_h$ = measure of the effective turbulence length scale in meters

$$= 1000\left(\frac{h}{10}\right)^{0.25} \tag{C6}$$

w = factor to account for the second order effects of turbulence intensity

$$= \frac{g_v r \sqrt{B}}{4} \tag{C7}$$

$g_f$ = a peak factor, the ratio of the expected peak value which occurs once per hour to the standard deviation of the resonant part of the fluctuating response

$$= \sqrt{2\ln(3600 n_a)} \tag{C8}$$

$n_a$ = first mode along-wind frequency of the structure in Hz

S = size factor accounting for the correlation of pressures over a structure

$$= \frac{1}{\left[1+\left(\frac{3.5 n_a h}{\overline{V}_h}\right)\right]\left[1+\left(\frac{4 n_a b}{\overline{V}_h}\right)\right]} \tag{C9}$$

$\overline{V}_h$ = design hourly mean wind speed at height *h*, in meters per second; note that in this dissertation a 2,000 year wind return period correction factor of 1.21 as determined from the SABS 0160:1989 Loading Code is applied for the reference case and subsequent technology evaluation. A factor of 1.13, corresponding to a 500 year return period wind, is applied for the ideal result.

E = spectrum of turbulence in the approaching wind stream

$$= \frac{0.47N}{\left(2+N^2\right)^{5/6}} \tag{C10}$$

N = effective reduced frequency

$$= \frac{n_a L_h}{\overline{V}_h} \tag{C11}$$

$\varsigma$ = structural damping ratio as a fraction of the critical damping ratio

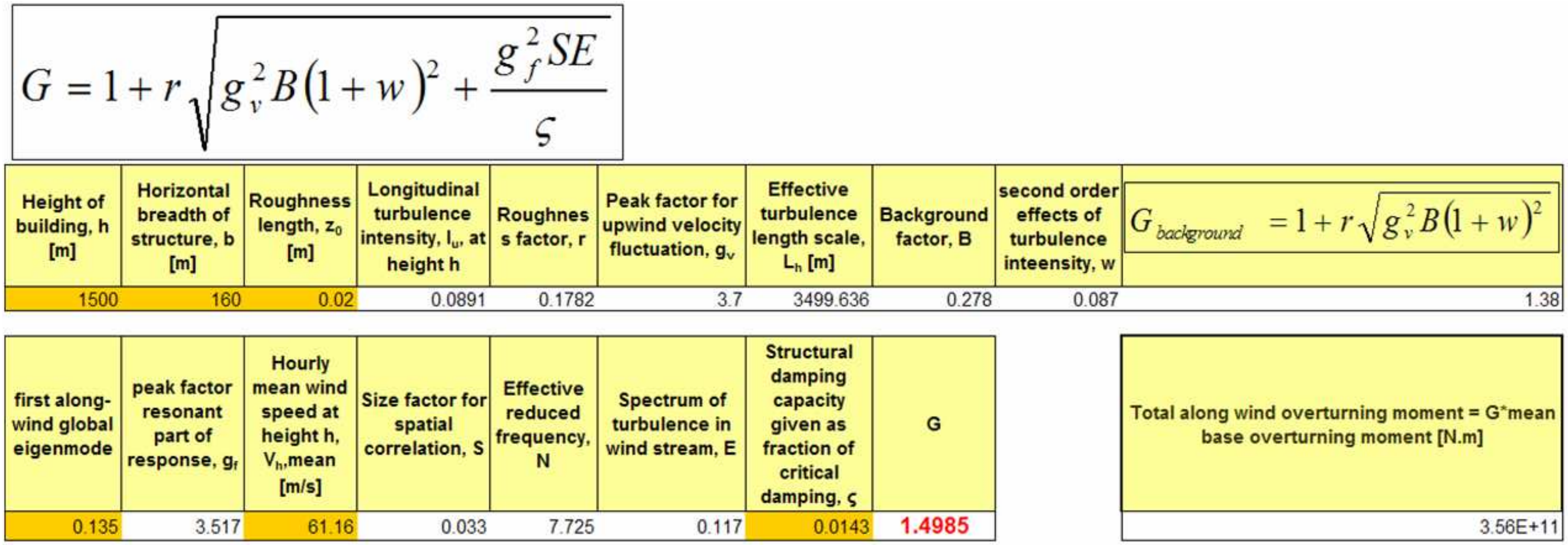
The ideal result for along wind response, based on a 500 year return period wind is provided in Table C-1.

Table C-1. Ideal case along wind base overturning moment.

| Parameter | Value | Reference |
|---|---:|---:|
| Height of building, h [m] | 1500 | Section 5.2.2 |
| Horizontal breadth of structure, b [m] | 160 | Section 5.2.2 |
| Roughness length, $z_0$ [m] | 0.02 | Appendix A |
| Longitudinal turbulence intensity, $I_u$, at height h | 0.0891 | Appendix A, eq13 |
| Roughness factor, r | 0.178 | Appendix C, eqC4 |
| Peak factor for upwind velocity fluctuation, $g_v$ | 3.7 | Appendix C |
| Effective turbulence length scale, $L_h$ [m] | 3499.6 | Appendix C, eqC6 |
| Background factor, B | 0.278 | Appendix C, eqC5 |
| Second order effects of turbulence intensity, w | 0.087 | Appendix C, eqC7 |
| Background response | 1.38 | Appendix C, eqC5 |
| First along-wind global free vibration mode | 0.135 | Appendix B, eqB13 |
| Peak factor resonant part of response, $g_f$ | 3.517 | Appendix C, eqC8 |
| Hourly mean wind speed at height h, $V_h$,mean [m/s] | 61.16 | Appendix A, eqA3 |
| Size factor for spatial correlation, S | 0.033 | Appendix C, eqC9 |
| Effective reduced frequency, N | 7.725 | Appendix C, eqC11 |
| Spectrum of turbulence in wind stream, E | 0.117 | Appendix C, eqC10 |
| Structural damping capacity given as fraction of critical damping, $\varsigma$ | 0.0143 | Section 7.2.8 |
| **Gust factor, G** | **1.4985** | Appendix C, eqC3 |
| Mean base overturning moment, [N.m] | 2.37e+11 | Appendix C, eqC2 |
| **Design peak base overturning moment, [N.m]** | **3.56e+11** | Appendix C, eqC1 |

The calculations for the reference case base overturning moment due to along wind excitation are shown by way of the following spreadsheet, in Figure C-2.

Table C-2. Calculations for the ideal case base overturning moment due to along wind excitation.



$$G = 1 + r\sqrt{g_v^2 B(1+w)^2 + \frac{g_f^2 SE}{\varsigma}}$$

| Height of building, h [m] | Horizontal breadth of structure, b [m] | Roughness length, $z_0$ [m] | Longitudinal turbulence intensity, $I_u$, at height h | Roughness factor, r | Peak factor for upwind velocity fluctuation, $g_v$ | Effective turbulence length scale, $L_h$ [m] | Background factor, B | second order effects of turbulence inteensity, w | $G_{background} = 1 + r\sqrt{g_v^2 B(1+w)^2}$ |
|---|---|---|---|---|---|---|---|---|---|
| 1500 | 160 | 0.02 | 0.0891 | 0.1782 | 3.7 | 3499.636 | 0.278 | 0.087 | 1.38 |

| first along-wind global eigenmode | peak factor resonant part of response, $g_f$ | Hourly mean wind speed at height h, $V_h$,mean [m/s] | Size factor for spatial correlation, S | Effective reduced frequency, N | Spectrum of turbulence in wind stream, E | Structural damping capacity given as fraction of critical damping, $\varsigma$ | G |
|---|---|---|---|---|---|---|---|
| 0.135 | 3.517 | 61.16 | 0.033 | 7.725 | 0.117 | 0.0143 | 1.4985 |

| Total along wind overturning moment = G*mean base overturning moment [N.m] |
|---|
| 3.56E+11 |

### C2.2 Excitation in across wind direction due to vortex induced across wind frequency force spectrum

Across wind resonance is excited by alternate vortex shedding in the wake of the chimney under constant velocity conditions. The type of vortex shedding pattern is subject to the flow regime, which is in turn a function of the wind velocity. The wind velocity at which vortex shedding frequency is the same as the structure's first global natural frequency, known as the *critical wind speed*, is described by [Holmes 2001]

$$V_{crit} = \frac{n_c b}{St} \tag{C12}$$

where $V_{crit}$ = critical wind velocity [m/s]

$n_c$ = first mode across-wind frequency of the structure [Hz]

b = breadth of the structure normal to the wind direction [m]

St = Strouhal number, which is characteristic of the vortex shedding frequency and varies for different flow-regimes

The Strouhal number for all heights of the chimney is based on two dimensional flow measurements. Figure C-2 depicts, for a smooth surface, and measurements at Reynolds numbers of larger than $1.10^7$ (typical for 160 meter diameter chimney), the Strouhal number to be 0.22. This value is then adapted for various ratios of distance-from-tip to diameter, in order to accommodate for three dimensional flow effects, according to [ESDU 1998]

$$St = St_{2D}\left[1 - 0.4e^{\frac{-1.6r}{D}}\right] \tag{C13}$$

where St = three dimensional Strouhal number

$St_{2D}$ = two dimensional Strouhal number, see Figure C-2

r = distance from tip of chimney [m]

D = diameter of chimney [m]

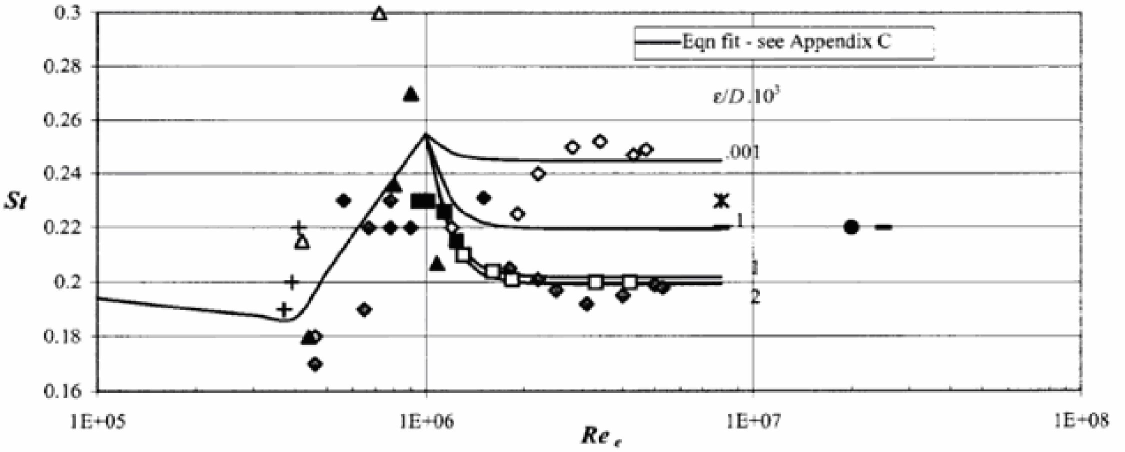


Figure C-2. Strouhal number change with Reynolds number (two dimensional flow) [ESDU 1998].

Results for a chimney diameter of 160 meter with the 2D Strouhal number equal to 0.22 are displayed in Figure C-3.

Lock-in behaviour occurs when the vortex shedding frequency is influenced by the natural frequency free vibration of the structure. It is prevalent in structures of 'relatively low stiffness' that has low damping ratios and operate 'near' the critical wind velocity [AS1170:2 1989]. The occurrence of lock-in is indicated with every technology alternative by a graph as in Figure C-4 – the crossing of the two lines would indicate potential lock-in behaviour, requiring further investigation.

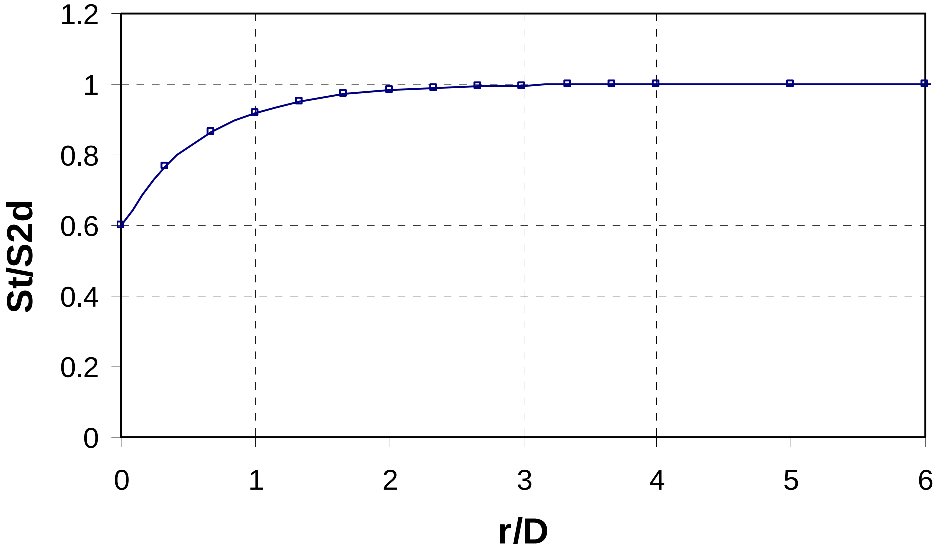


Figure C-3. Three dimensional Strouhal number changes with distance from chimney tip.

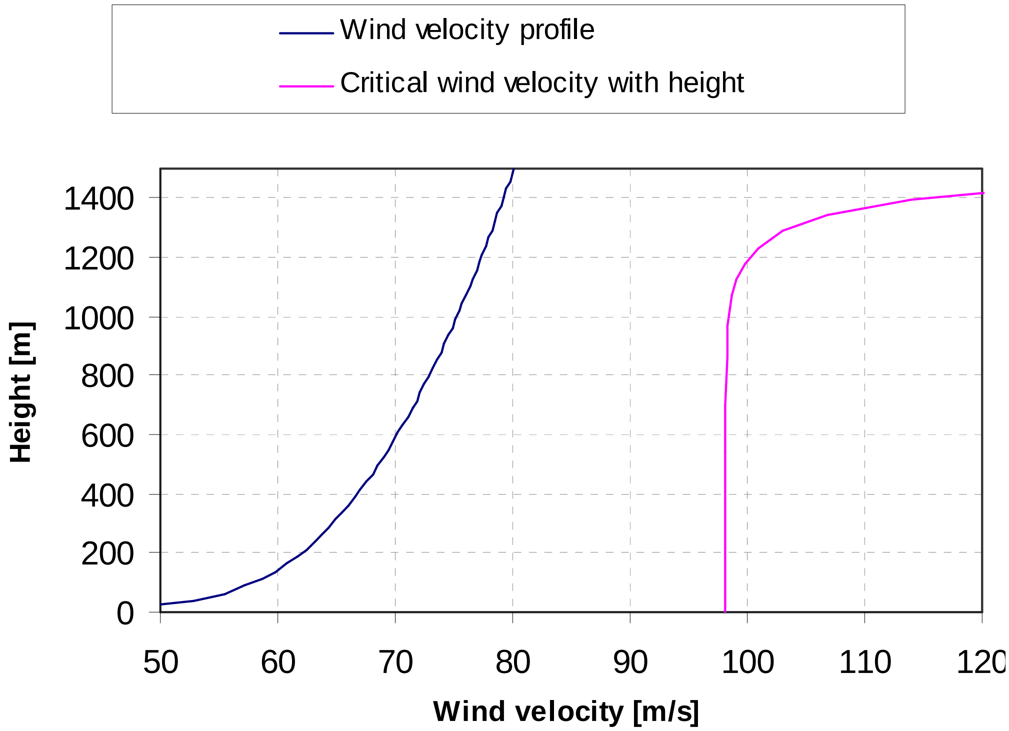


Figure C-4. Typical graph indicating proximity of actual wind velocities (blue line) to the critical wind velocities (pink line). Note that the 2,000 year return period wind is used in determining the actual velocity profile.

The design peak base overturning moment in the cross-wind direction generated by this type of dynamic excitation is formulated by the AS1170-2:1989 as follows:

$$\hat{M}_c = 0.5 g_f \bar{q}_h b h^2 (1.06 - 0.06k) \sqrt{\left(\frac{\pi C_{fs}}{\varsigma}\right)} \quad \text{(C14)}$$

where $\hat{M}_c$ = design peak base overturning moment in the cross-wind direction

$g_f$ = a peak factor

= $\sqrt{2\ln(3600 n_c)}$ (C15)

$\bar{q}_h$ = hourly mean dynamic wind pressure at height *h* [Pa]

= $\frac{1}{2}\rho_z \bar{U}_z^2$ (C16)

$\rho_z$ = air density at relevant height [kg/m$^3$]

$\overline{U}_z$ = mean design wind velocity at height $z$ [m/s] (described by equation B3)

h = height of the structure [m]

k = a mode shape power exponent from representation of the fundamental mode shape by $\psi(z) = (z/h)^k$; with k ≈ 2.3 for a tower decreasing in stiffness with height [AS1170:2 1989]. A verifying investigation finds this value to be closer to 2.4 – Figure C-5 presents an exponential curve fit on the first global free vibration mode shape (reference case). The eigen vector values along the height were chosen on the zero degree position, i.e. the position facing the wind direction; these are plotted against the height. The fitted exponential curve reveals an exponent of 2.4 to fit the curve the best.

$C_{fs}$ = cross-wind force spectrum coefficient due to vortex shedding, generalised for a linear mode, as from Figure C-6, read off at reduced velocity = $U_{\text{design hourly mean, h}} / (n_c \cdot b)$ (C17)

$n_c$ = fundamental mode frequency in cross wind direction [Hz]

b = width of structure [m]

$\varsigma$ = structural damping ratio as a fraction of the critical damping ratio

The ratio of $\hat{M}_c : \overline{M}_c$ provides an quasi-static design factor on base overturning moment providing for across wind resonance. (C15)

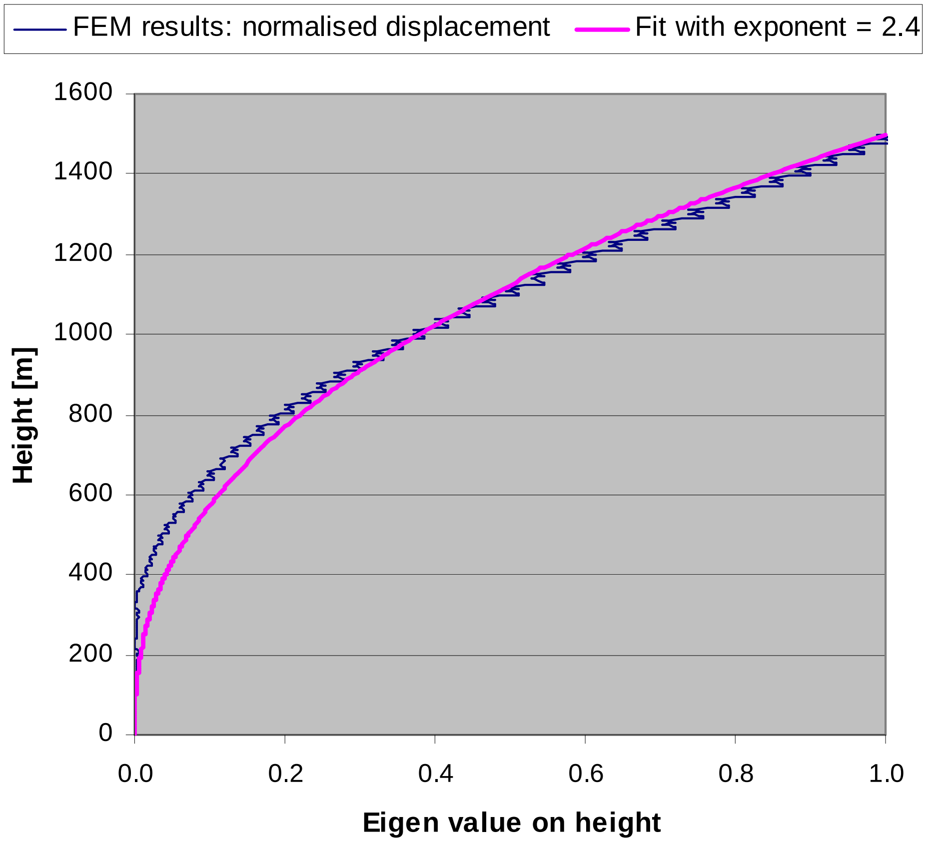


Figure C-5. Curve fit to SCPP chimney first global free vibration mode.

Currently, as Kijewski and Kareem [2001] points out the force spectrum (Figure C-6) is determined from provided spectra for only a limited number of shapes and aspect ratios. As a result, interpolation is used if the desired aspect ratio does not correspond to those provided; the nearest shape must be selected to approximate the force spectrum coefficient if the desired shape is not available. As wind tunnel tests on several buildings of varying dimension have shown, the spectra can vary greatly, so the interpolation of a given spectrum adds some uncertainty to the across wind estimate. The across wind force spectral amplitude is sensitive to the level of turbulence in the approach flow and the building aspect ratio.

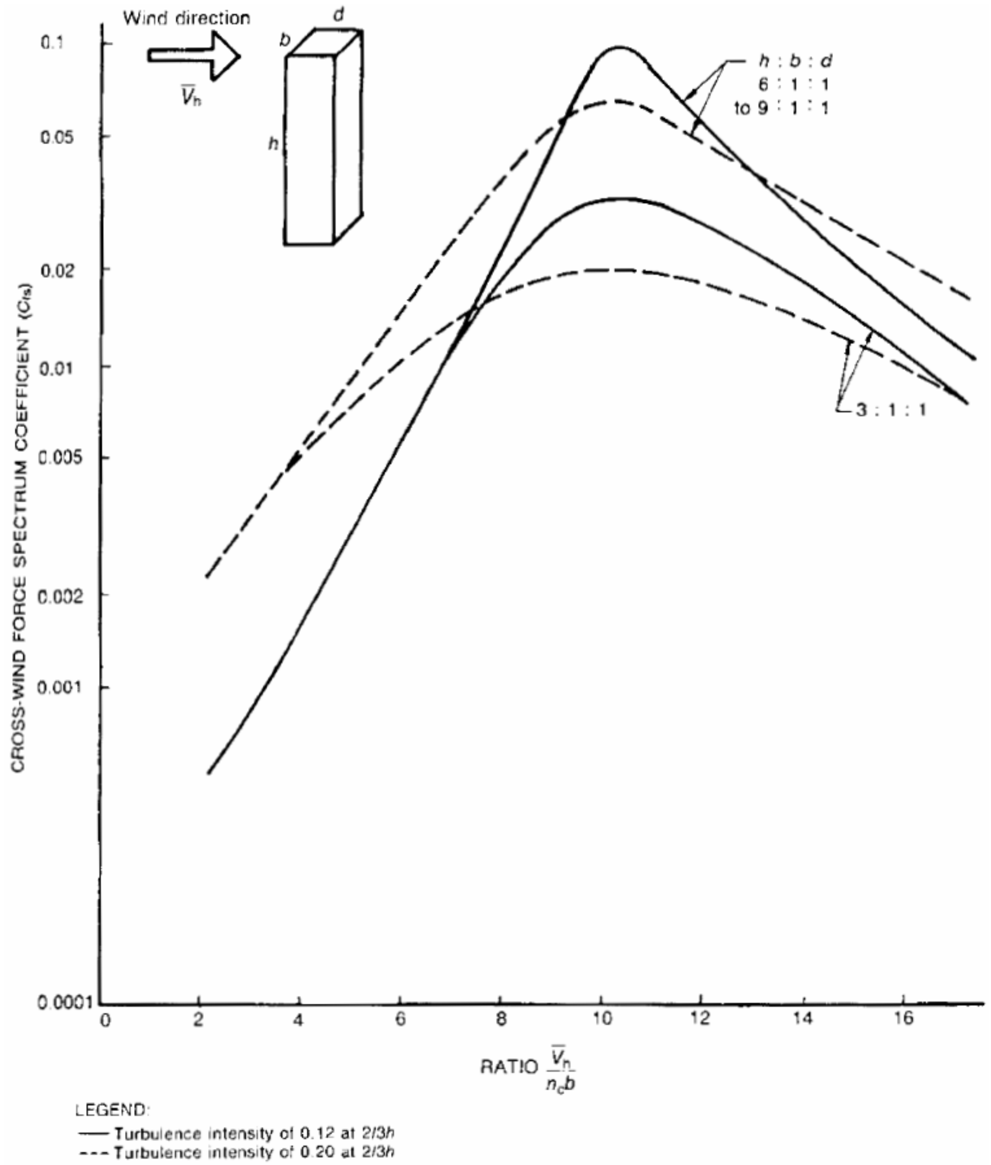


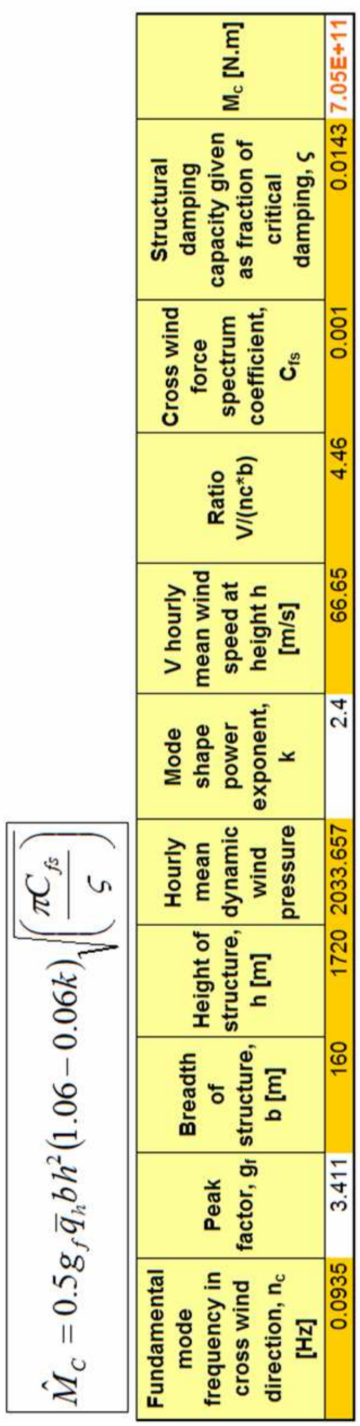
Figure C-6. Cross wind force spectrum for square cross-section buildings [AS1170:2 1989].

An example of the calculations for the base overturning moment due to across wind excitation is shown in Table C-3 and C-4.

Table C-3. Calculated values for the across wind base overturning moment for cross wind force investigation.

| **Parameter** | **Value** | **Reference** |
|---|---|---|
| Fundamental mode frequency in cross wind direction, $n_c$ [Hz] | 0.094 | Appendix B, eqB13 |
| Peak factor, $g_f$ | 3.411 | Appendix C, eqC12 |
| Width of structure, b [m] | 160 | Section 5.2.2 |
| Height of structure, h [m] | 1,720 | Section 5.2.2 |
| Hourly mean dynamic wind pressure [Pa] | 2,033.66 | Appendix C, eqC13 |
| Mode shape power exponent, k | 2.4 | Appendix C2 |
| Hourly mean wind speed, $U_{\text{design hourly mean, h}}$ [m/s] | 66.65 | Appendix A, eqA3 |
| Ratio $U_{\text{design hourly mean, h}} /(n_c \cdot b)$ | 4.46 | Appendix C, eqC14 |
| Cross wind force spectrum coefficient, $C_{fs}$ | 0.001 | Appendix C2 |
| Structural damping capacity given as fraction of critical damping, $\varsigma$ | 0.0143 | Appendix C2 |
| **Design across peak base overturning moment [N.m]** | **7.05e+11** | Appendix C, eqC11 |
| **Across resonance peak factor on base overturning moment** | **1.9483** | Appendix C, eqC15 |

Table C-4. Calculations for the across wind base overturning moment for cross wind force spectrum model.



$$\hat{M}_C = 0.5 g_f \bar{q}_h b h^2 (1.06 - 0.06k)\sqrt{\left(\frac{\pi C_{fs}}{\varsigma}\right)}$$

| Fundamental mode frequency in cross wind direction, $n_c$ [Hz] | Peak factor, $g_f$ | Breadth of structure, b [m] | Height of structure, h [m] | Hourly mean dynamic wind pressure | Mode shape power exponent, k | V hourly mean wind speed at height h [m/s] | Ratio V/(nc*b) | Cross wind force spectrum coefficient, $C_{fs}$ | Structural damping capacity given as fraction of critical damping, ς | $M_c$ [N.m] |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.0935 | 3.411 | 160 | 1720 | 2033.657 | 2.4 | 66.65 | 4.46 | 0.001 | 0.0143 | 7.05E+11 |

## References

ESDU (Engineering Science Data Unit) (1998), *Response of structures to vortex shedding – structures of circular or polygonal cross section*, HIS Standards Store.

# APPENDIX D

# SCPP CHIMNEY COST MODEL

## D1 Chimney costs

### D1.1 Unit costs

The cost of the chimney is a function of the volume of material used, the specific material cost, the construction cost and transport cost. The chimney is constructed of thin shell reinforced high performance concrete.

For the purpose of the reference evaluation the cost structures in Tables D1 are used – these are based on construction costs of tall reinforced concrete chimneys, obtained from a well-known South African civil contractor [Grinaker-LTA 2005]. A volume based approach is used, i.e. materials are assigned physical, labour, plant and logistical cost per volume. For the chimney shell and fin stiffeners (referred to as “high level construction”), a high performance concrete cost of R1,000/m$^3$ is used. Low elevation construction (foundations) uses normal performance concrete at R800/m$^3$ and shows a decrease in labour and logistical cost. Structural steel construction at high elevation, for example the circumferential stiffener placement, is also portrayed in Table D-1. Labour and logistical costs associated with high elevation construction are significantly higher than for low elevation construction.

The detailed nature of this model lends itself to easy navigation into and investigation of how conceptual or parametrical (technology) changes in the system influences overall chimney system cost.

### D1.2 Reference case chimney cost

A chimney of 1,500 meter height and 160 meter diameter is investigated with geometry as specified in the Chapter 5 reference case (section 5.2.2). Each circumferential stiffener consists of 72 flat structural steel beams, each of 0.63 × 0.06 meter cross-section, spanning the radius from a stiff outer ring of the same cross section at the chimney perimeter to a connector hub at the centre of the stiffener arrangement [Van Dyk and Van Zijl 2002]. The capital cost of the reference case chimney system is calculated as R27.70Bn. See Table D-2 for a breakdown of the costs.

Table D-1. Reference case cost assumptions

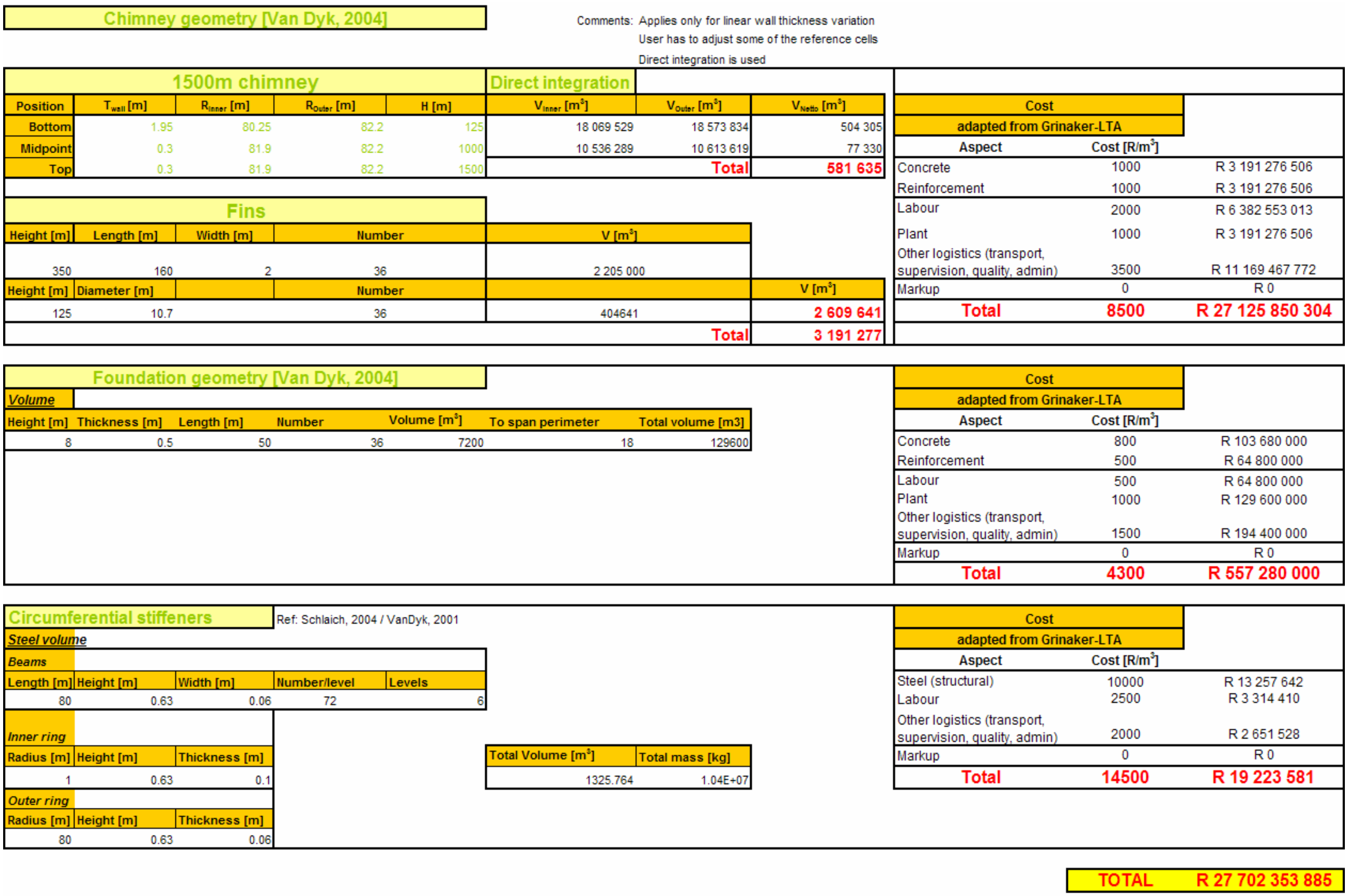
| | High elevation concrete | Low elevation concrete | High elevation steel |
|---|---|---|---|
| **Aspect** | **Cost [R/m$^3$]** | | |
| Material | 1,000 | 800 | 10,000 |
| Reinforcement | 1,000 | 500 | n/a |
| Labour | 2,000 | 500 | 2,500 |
| Plant | 1,000 | 1,000 | n/a |
| Other logistics (transport, supervision, quality, admin) | 3,500 | 1,500 | 2,000 |
| **Total** | **8,500** | **4,300** | **14,500** |

The fin structure cost (80%) largely outweighs the chimney shell (18%) and foundation (2%) costs. The circumferential stiffener cost contribution is negligible.

Figure D-1 displays the spreadsheet used for calculation of the reference case cost. A digital version of this (and each alternative technology's) cost calculation is available from the US-ISE.

Table D-2. Cost breakdown of reference case SCPP chimney.

| | Volume [m$^3$] | Unit cost [R/m$^3$] | Cost |
|---|---|---|---|
| **Chimney** | 581,635 | 8,500 | R 4,943,901,288 |
| **Fins** | 2,609,641 | 8,500 | R 22,181,949,017 |
| **Foundation** | 129,600 | 4,300 | R 557,280,000 |
| **Circumferential stiffener** | 1,326 | 14,500 | R 19,223,581 |
| | | | R 27,702,353,885 |



**Chimney geometry [Van Dyk, 2004]**

Comments: Applies only for linear wall thickness variation
User has to adjust some of the reference cells
Direct integration is used

**1500m chimney** | **Direct integration**

| Position | $T_{wall}$ [m] | $R_{inner}$ [m] | $R_{outer}$ [m] | H [m] | $V_{inner}$ [m$^3$] | $V_{outer}$ [m$^3$] | $V_{Netto}$ [m$^3$] |
|---|---|---|---|---|---|---|---|
| Bottom | 1.95 | 80.25 | 82.2 | 125 | 18 069 529 | 18 573 834 | 504 305 |
| Midpoint | 0.3 | 81.9 | 82.2 | 1000 | 10 536 289 | 10 613 619 | 77 330 |
| Top | 0.3 | 81.9 | 82.2 | 1500 | | Total | 581 635 |

**Fins**

| Height [m] | Length [m] | Width [m] | Number | V [m$^3$] | |
|---|---|---|---|---|---|
| 350 | 160 | 2 | 36 | 2 205 000 | |
| Height [m] | Diameter [m] | | Number | | V [m$^3$] |
| 125 | 10.7 | | 36 | 404641 | 2 609 641 |
| | | | | Total | 3 191 277 |

| Cost<br>adapted from Grinaker-LTA | | |
|---|---|---|
| Aspect | Cost [R/m$^3$] | |
| Concrete | 1000 | R 3 191 276 506 |
| Reinforcement | 1000 | R 3 191 276 506 |
| Labour | 2000 | R 6 382 553 013 |
| Plant | 1000 | R 3 191 276 506 |
| Other logistics (transport, supervision, quality, admin) | 3500 | R 11 169 467 772 |
| Markup | 0 | R 0 |
| Total | 8500 | R 27 125 850 304 |

**Foundation geometry [Van Dyk, 2004]**

*Volume*

| Height [m] | Thickness [m] | Length [m] | Number | Volume [m$^3$] | To span perimeter | Total volume [m3] |
|---|---|---|---|---|---|---|
| 8 | 0.5 | 50 | 36 | 7200 | 18 | 129600 |

| Cost<br>adapted from Grinaker-LTA | | |
|---|---|---|
| Aspect | Cost [R/m$^3$] | |
| Concrete | 800 | R 103 680 000 |
| Reinforcement | 500 | R 64 800 000 |
| Labour | 500 | R 64 800 000 |
| Plant | 1000 | R 129 600 000 |
| Other logistics (transport, supervision, quality, admin) | 1500 | R 194 400 000 |
| Markup | 0 | R 0 |
| Total | 4300 | R 557 280 000 |

**Circumferential stiffeners** Ref: Schlaich, 2004 / VanDyk, 2001

*Steel volume*

*Beams*

| Length [m] | Height [m] | Width [m] | Number/level | Levels |
|---|---|---|---|---|
| 80 | 0.63 | 0.06 | 72 | 6 |

*Inner ring*

| Radius [m] | Height [m] | Thickness [m] |
|---|---|---|
| 1 | 0.63 | 0.1 |

*Outer ring*

| Radius [m] | Height [m] | Thickness [m] |
|---|---|---|
| 80 | 0.63 | 0.06 |

| Total Volume [m$^3$] | Total mass [kg] |
|---|---|
| 1325.764 | 1.04E+07 |

| Cost<br>adapted from Grinaker-LTA | | |
|---|---|---|
| Aspect | Cost [R/m$^3$] | |
| Steel (structural) | 10000 | R 13 257 642 |
| Labour | 2500 | R 3 314 410 |
| Other logistics (transport, supervision, quality, admin) | 2000 | R 2 651 528 |
| Markup | 0 | R 0 |
| Total | 14500 | R 19 223 581 |

**TOTAL** R 27 702 353 885

Figure D-1. Sheet used to calculate the chimney costs.

## D2 Collector costs

A plastic-based collector is chosen on the basis of lower construction costs. Note that the thermal properties of plastic are presumably less favourable for heat loss and storage than glass with a negative impact on the plant energy generation capacity. These losses are, for the purpose of this thesis, assumed to be negligible, i.e. it is assumed that the plastic thermal and durability performance is on par with that of glass.

The main assumptions for the collector cost model presented in this paper are:

- The transparent material comprises a durable plastic membrane, priced at R10/m$^2$
- The roof supporting truss system costs R20/m$^2$.
- The roof supporting truss system contains load absorption measures sufficient to circumvent all wind and temperature related action.
- The airflow drag due to column cross-section is negligible, therefore the cheapest column cross-section is chosen, not concerning aerodynamic shape. The sections are approximated as IPE120$_{AA}$ sections, used throughout the collector. It is assumed that these sections can be sufficiently braced against buckling. Their cost is assumed at R100/m.
- The cost of the column foundations is assumed to be the same as for the chimney “low elevation concrete” in Table D-1.
- The transport cost is assumed to be 5% of the material cost.
- The labour and plant costs are estimated to be 100% of the collector material cost.

The collector consists of a transparent roof elevated by a support structure. The roof extends from the outer perimeter of the collector to a radius of 200 meter from the centre of the chimney. It has an outer diameter of 6,900 meter. The support structure consists of steel columns supporting a truss-work system from which the plastic is suspended. The collector has an inlet height of 3 meters and rises exponentially (exponent = 0.827) to a height of 32 meters at 200 meter radius. A volume of 0.192 m$^3$ concrete is required per column foundation.

Table D-3 reports the cost breakdown of the SCPP collector. A total cost of R2.53Bn is calculated.

Table D-3. Cost breakdown of the SCPP collector.

| Part | Cost |
|---|---|
| Column cost | R 84,798,377 |
| Truss cost | R 767,176,926 |
| Glass cost | R 383,588,463 |
| Column foundation | R 151,255,673 |
| Circumferential stiffener cost | negl. |
| Collector material cost | R 1,235,563,766 |
| Transport | R 61 778 188 |
| Labour | R 1 235 563 766 |
| **Total collector cost** | **R 2 532 905 720** |

## D3 System cost summary and electricity cost

The cost of the power conversion unit (turbines, generators, flow ducts, structure, etc.) is estimated at R1.20Bn. The total cost of the system is R31.44Bn of which the chimney system contributes 88%. Radical reduction in chimney cost can therefore greatly improve the financial feasibility of the SCPP. The total costs are summarised in Table D-4.

Table D-4. Summary of costs of the SCPP reference case.

| Part | Cost [RBn] |
|---|---|
| Chimney system | 27.70 |
| Collector cost | 2.53 |
| Power conversion unit cost | 1.20 |
| **Total investment cost** | **31.44** |

The LEC (levelised electricity cost) is calculated using the cost model presented in a paper by Fluri et al. [2006]. The operating and maintenance cost is assumed at R38Mn annually. This operating and maintenance cost is double the (equivalent) R19Mn annually reported by Schlaich, which is based on a 100 MW SCPP plant (half the reference case output) [Schlaich et al. 2004b].

The present equivalent value of these costs over the lifetime of the plant is found with Equation D1.

$$P = \frac{A_1}{f - i}\left[\left(\frac{1+f}{1+i}\right)^N - 1\right] = \frac{38{,}000{,}000}{0.06 - 0.08}\left[\left(\frac{1+0.06}{1+0.08}\right)^{80} - 1\right] = R1{,}469{,}938{,}350 \qquad \text{(D1)}$$

where $A_1$ is the cash flow at the end of the first year, $f$ is the inflation rate, $i$ is the interest rate and N is the lifetime in years. This equivalent annual cost is calculated using a depreciation period of 80 years, an interest rate of 8.0% and an inflation rate[i] of 6.0%. The lifetime operating and maintenance cost is added to the capital cost to determine the total present value over the lifetime of the project. An equivalent annual cost over the project lifetime can be calculated according to Equation D2.

$$A = P\left[\frac{i(1+i)^N}{(1+i)^N - 1}\right] = (31{,}435{,}259{,}605 + 1{,}469{,}938{,}350)\left[\frac{0.08(1+0.08)^{80}}{(1+0.08)^{80} - 1}\right] = R2{,}638{,}005{,}366 \qquad \text{(D2)}$$

The levelised electricity cost (LEC) is ascertained by dividing the equivalent annual cost by the annual power output (305.04 GWh, generated by the 200 MW SCPP plant [Bernardes 2008 – refer to Appendix E for more detail]) as shown in Equation D3.

$$LEC = \frac{2{,}638{,}005{,}366}{305{,}040{,}000} = R8.65 / kWh \qquad \text{(D3)}$$

Note that the LEC is very sensitive to economic variables like interest and inflation. An interest rate decreased to 6.0% yields an LEC of R6.81/kWh. The cost model is summarised in Table D-5.

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[i] The inflation rate chosen is used in the publication by Fluri et al. [2006].

Table D-5. SCPP levelised electricity cost results.

| **Plant specifications** | | Ref | **Equivalent annual cost (EAC)** | Ref |
|---|---|---|---|---|
| Nominal power [MW] | 200 | Specified | R 2 638 005 366 | Eq D2 |
| Annual power output [GWh/a] | 305.04 | Bernardes | | |
| | | | **Levelised Electricity Cost (LEC) [R/kWh]** | |
| **Cost specifications** | | | 8.65 | Eq D3 |
| Capital cost | R 31 435 259 605 | Determined | | |
| Operation and maintenance cost (1st year) | R 38 000 000 | Schlaich et al. 2004b | | |
| Cumulative present value of operation and maintenance | R 1 469 938 350 | Eq D1 | | |
| Interest rate | 8.0% | | | |
| Inflation rate | 6.0% | | | |
| Depreciation period [years] | 80 | | | |

## References

Fluri, T.P., Pretorius, J.P., Van Dyk, C., Von Backström, T.W., Kröger, D.G., Van Zijl, G.P.A.G. (2006), *Cost analysis of solar chimney power plants*, EUROSUN 2006, Glasgow, June 2006.

Bernardes, M.A. dos S. (2008), Personal correspondence based on the SCPP performance model developed at the US-ISE.

Grinaker-LTA (2005), Personal correspondence with Mr. Christo Schoeman.

# APPENDIX E

# SCPP SYSTEM ENERGY YIELD

## E1 Introduction on energy yield simulation model

A simulation program [Bernardes 2008] is used to solve the thermo-flow field in the collector and chimney of the SCPP. The relevant equations for conservation of mass, momentum and energy are solved simultaneously using finite difference methods. Meteorological data (ambient air temperature, humidity, solar irradiation and wind speed) from Sishen, South Africa, is used as input to the simulation. Factors such as the position of the sun throughout the year at the particular global location, shadow cast by the chimney and all frictional, inlet, outlet, support and heat losses are also taken into account. At the time of writing this dissertation, the Bernardes simulation model [2008] was unpublished. However, it is based on the simulation model by Pretorius and Kröger [2006]. The detail of the Bernardes model falls outside the scope of this dissertation. The thermo-flow and geometrical parameters used in the SCPP reference case energy yield simulation in this study are summarised in Table E-1.

Table E-1. Thermo-flow and geometrical parameters for SCPP reference case simulation.

| **Parameters** | **Value** | **Unit** |
|---|---|---|
| **Computational parameters** | | |
| Volumes | 30 | [ - ] |
| Time interval | 3600 | [s] |
| **Collector** | | |
| Roof shape exponent | 1.0 | [ - ] |
| Perimeter (inlet) height | 5.0 | [m] |
| Emissivity of roof | 0.87 | [ - ] |
| Emissivity of absorber | 0.90 | [ - ] |
| Extinction coefficient of roof | 4 | [1/m] |
| Refractive index of roof | 1.526 | [ - ] |
| Thickness of roof | 0.004 | [ - ] |

| | | |
|---|---|---|
| Outer diameter | 5000 | [m] |
| Inner diameter | 400 | [m] |
| Inlet loss coefficient | 1 | [m] |
| Support diameter | 0.2 | [m] |
| Support drag coefficient | 1 | [ - ] |
| Supports tangential pitch | 10 | [m] |
| Supports radial pitch | 10 | [m] |
| Absorber roughness | 0.05 | [m] |
| Heat transfer scheme | Bernardes | |

### Chimney

| | | |
|---|---|---|
| Chimney height | 1500 | [m] |
| Chimney diameter | 160 | [m] |
| Chimney base | 160 | [m] |
| Wall roughness | 0.002 | [m] |
| Circumferential stiffener pressure coefficient | 0.01 | [ - ] |
| Number of circumferential stiffeners | 6 | [ - ] |

### Turbine

| | | |
|---|---|---|
| Turbine inlet loss coefficient | 0.14 | [ - ] |
| Turbo-generator efficiency | 0.80 | [ - ] |
| Control scheme | “x-factor” | |
| X-factor | 0.93 | [ - ] |

### Ground

| | | |
|---|---|---|
| Density | 2160 | [kg/m³] |
| Specific heat | 710 | [J/kg·K][i] |
| Thermal conductivity | 1.83 | [W/m·K][ii] |
| Absorptivity | 0.90 | [ - ] |
| Depth | 2 | [m] |
| Nodes | 20 | [ - ] |

### Local parameters

| | | |
|---|---|---|
| Longitude | 0 | [°] |
| Latitude | -20 | [°] |
| Local pressure | 90000 | [Pa] |
| Horizontal visibility | 100000 | [m] |
| Cirrus thickness | 0.1 | |
| Surface albedo | 0.35 | [ - ] |
| Day number | 1 | |
| Geographic length referring to the local standard time | -15 | [°] |

---

[i] Specific heart coefficient in Joule per kilogram-Kelvin (unit of thermal conductivity).
[ii] Thermal conductivity rating in Watt per meter-Kelvin (unit of absorptivity).

For the SCPP reference case geometry the annual yield is simulated and calculated at 305.04 GWh/y. Subsequent energy yield simulations determined the impact of most of the technologically augmented alternatives; some of which could not be incorporated due to resource constraints.

## References

Pretorius, J.P. and Kröger (2006), *Solar chimney power plant performance*, ASME, Vol. 128, August 2006

Bernardes, M.A. dos S. (2008), Personal correspondence based on the SCPP performance model developed at the US-ISE.

# APPENDIX F

# UPPER BOUNDARY LAYER WIND DATA FROM THE SOUTH AFRICAN WEATHER BUREAU

Upper boundary layer wind data was acquired from the South African Weather Bureau for the Upington (near Sishen) and De Aar (south eastern tip of the Northern Cape) weather stations [WeatherSA 2007]. Weather balloons are released and wind velocity measured and sent back to the ground station every ten seconds. This data is recorded in digital format. The data was plotted – geopotential meters[i] against velocity, as is displayed in Figure F-1 – and revealed velocity fluctuation “spikes” indicating *linear* increase and decrease of velocities instead of an anticipated non-linear fluctuation. This fact was pointed out to the Weather Bureau which they referred to their technical staff. The data discredit issue could not be resolved within the allocated resources and was set aside until more credible substantiation of the directional variation is found.

## References

WeatherSA (2007), Personal correspondence with Mrs. Tracey Gill.

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[i] Geopotential height is an adjustment to geometric height (elevation above mean sea level) using the variation of gravity with latitude and elevation.

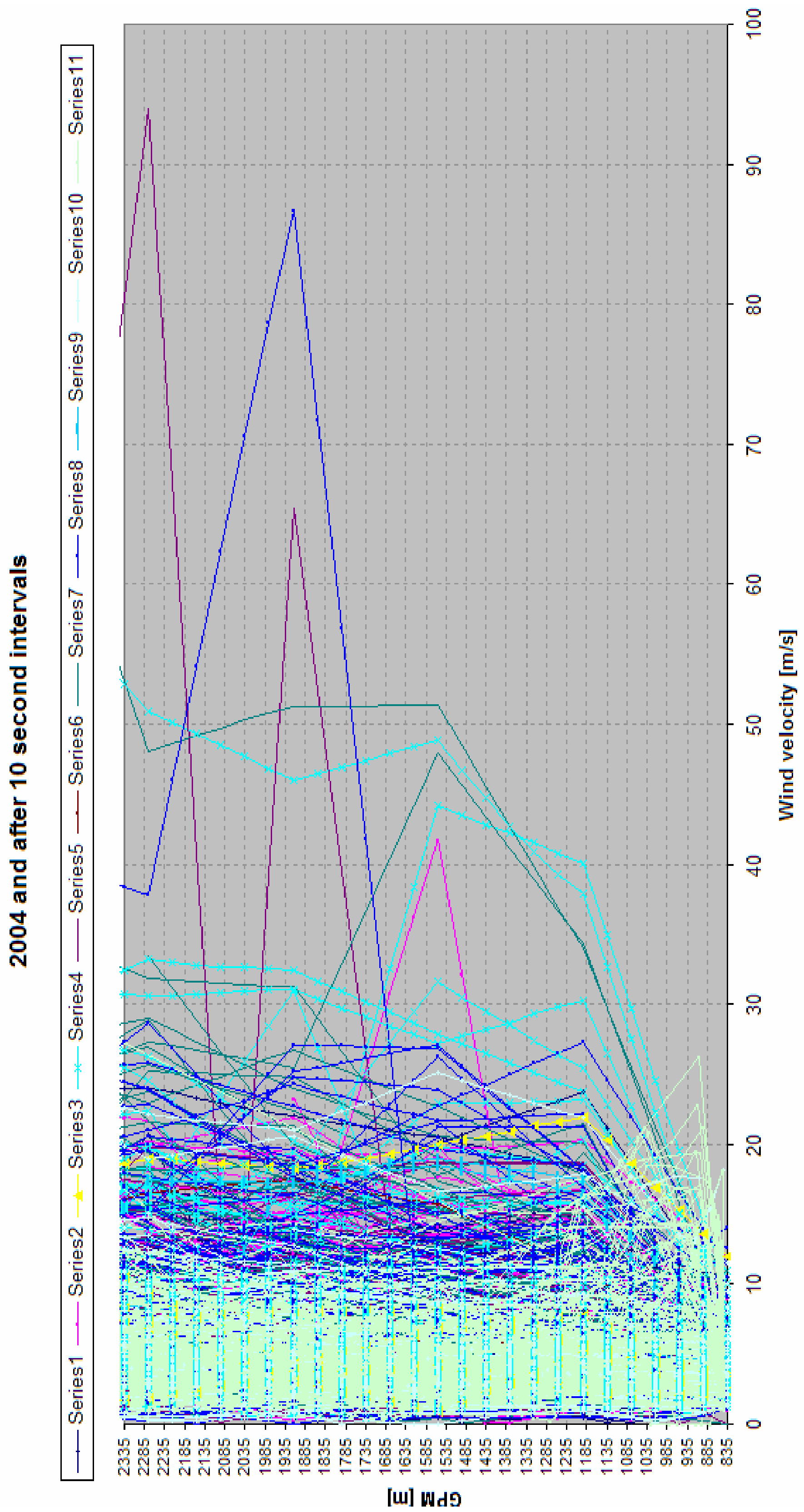


Figure F-1. Graph depicting wind velocity measurements over various heights at Upington for 2004 and after.

# APPENDIX G

# CALCULATIONS FOR EVALUATION OF SCPP CHIMNEY SYSTEM PERFORMANCE

## G1 Introduction

In the evaluation phase of the RIM, the reference case and, subsequently, all identified alternatives are evaluated in terms of specified criteria. Each technology augmentation of the SCPP chimney on the system, as identified in section 7.2, is evaluated here. This Appendix provides the results of the various improvements on the system performance. For each alternative the energy yield, capital cost, their incorporation into a levelised electricity cost and the structural performance (critical buckling factor and quasi-static structural response factor) is reported. The calculations for the reference case results are shown in the following sections:

- The capital cost calculations for the reference case SCPP are reported in Appendix D1 (chimney) and D2 (collector and power conversion unit).
- Levelised electricity cost calculations for the reference case are calculated and reported in Appendix D3.
- Buckling analysis procedures are reported in Appendix A and are calculated for each alternative using FEM.
- Base overturning moment due to along and across wind excitation is calculated for the ideal case and the increased chimney height model, and reported in Appendix C.

## G2 Calculations and results for alternatives

### G2.1 Reference model

Energy yield

The simulation program reported in Appendix F calculates an annual energy yield of 305.04 GWh/y. Note that this program is used for all the energy yield calculations.

Capital cost

A detailed cost model with all its assumptions was set up and reported in Appendix D. The capital cost of the reference case chimney system is calculated as R27.70Bn. See Table D-2 for a breakdown of the costs.

A levelised electricity cost (LEC) of R8.648/kWh is calculated for the SCPP system.

Structural performance

The load case incorporating gravity load, peak gust wind load and internal pressure load is applied in a linear elastic buckling analysis yielding a first global buckling value of $\lambda_1 = 1.63$. Figure G-1 depicts the nature of this buckling mode: global shell buckling.

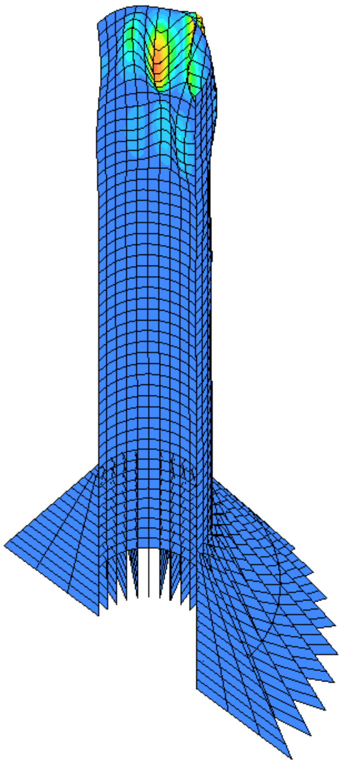


Figure G-1. SCPP chimney reference case first buckling mode.

A free vibration analysis is performed. The first global free vibration frequency calculated is $f_{1,\mathrm{global}}$ = 0.135 Hz (Appendix A, equation A3). No second global free vibration modes are present in the spectrum below 0.2 Hz. Some more localised ovallising modes are present at $f_{1,\mathrm{local}}$ = 0.129 and $f_{2,\mathrm{local}}$ = 0.224 Hz and are depicted in Figure G-2. There is therefore no danger of a second resonant response peak – the simplified dynamic gust peak method may be used.

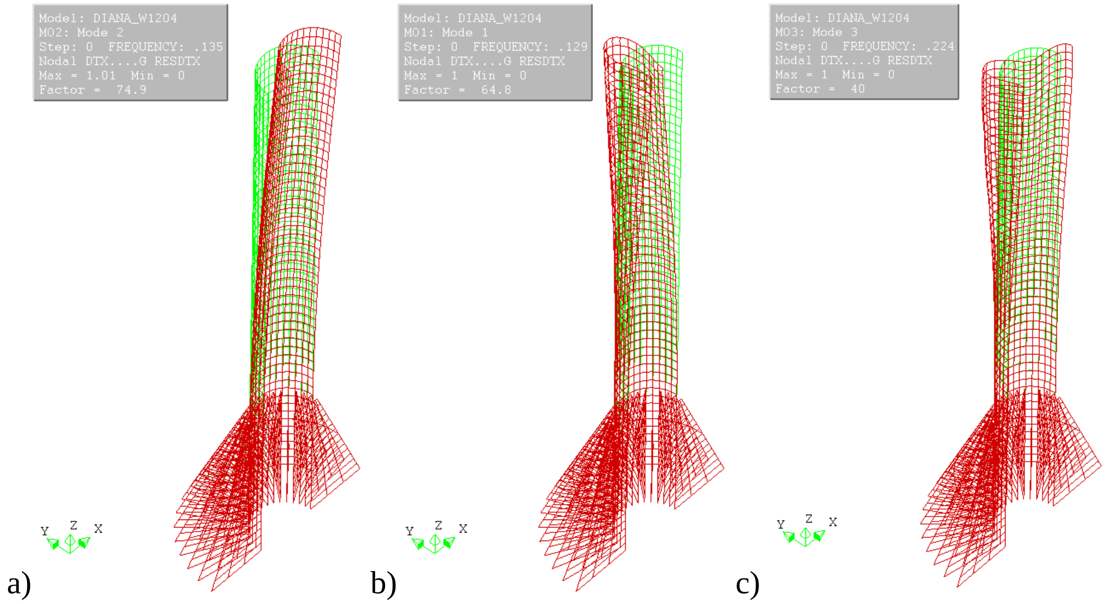


Figure G-2. Free vibration modes of the SCPP chimney: a) first global mode; b) first and c) second local modes.

The calculations for the along wind gust factor, *G*, follow. Relevant values for the reference case are presented in Table G-1. All the parameter and equation references are provided in the column on the right.

The across wind moment calculation is not necessary because the critical wind velocities are far outside any point on the wind velocities profile – see Figure G-3 – and, hence, are not a threat to structural integrity (refer to Appendix C, equation C12). This appendix further only provides the figure depicting the proximity of the wind velocity profile to the critical wind velocity profile when it is of interest.

Table G-1. Reference case along wind base overturning moment.

| Parameter | Value | Reference |
|---|---|---|
| Height of building, h [m] | 1,500 | Section 5.2.2 |
| Horizontal width of structure, b [m] | 160 | Section 5.2.2 |
| Roughness length, $z_0$ [m] | 0.02 | Appendix A |
| Longitudinal turbulence intensity, $I_u$, at height h | 0.0891 | Appendix A, eq13 |
| Roughness factor, r | 0.178 | Appendix C, eqC4 |
| Peak factor for upwind velocity fluctuation, $g_v$ | 3.7 | Appendix C |
| Effective turbulence length scale, $L_h$ [m] | 3,499.6 | Appendix C, eqC6 |
| Background factor, B | 0.278 | Appendix C, eqC5 |
| Second order effects of turbulence intensity, w | 0.087 | Appendix C, eqC7 |
| Background response | 1.38 | Appendix C, eqC5 |
| First along-wind global free vibration mode | 0.135 | Appendix B, eqB13 |
| Peak factor resonant part of response, $g_f$ | 3.517 | Appendix C, eqC8 |
| Hourly mean wind speed at height h, $V_{h,mean}$ [m/s] | 65.03 | Appendix A, eqA3 |
| Size factor for spatial correlation, S | 0.036 | Appendix C, eqC9 |
| Effective reduced frequency, N | 7.265 | Appendix C, eqC11 |
| Spectrum of turbulence in wind stream, E | 0.121 | Appendix C, eqC10 |
| Structural damping capacity given as fraction of critical damping, $\varsigma$ | 0.0143 | Section 7.2.8 |
| **Gust factor, G** | **1.5129** | Appendix C, eqC3 |
| Mean base overturning moment [N.m] | 2.69e+11 | Appendix C, eqC2 |
| **Design peak base overturning moment [N.m]** | **4.07e+11** | Appendix C, eqC1 |

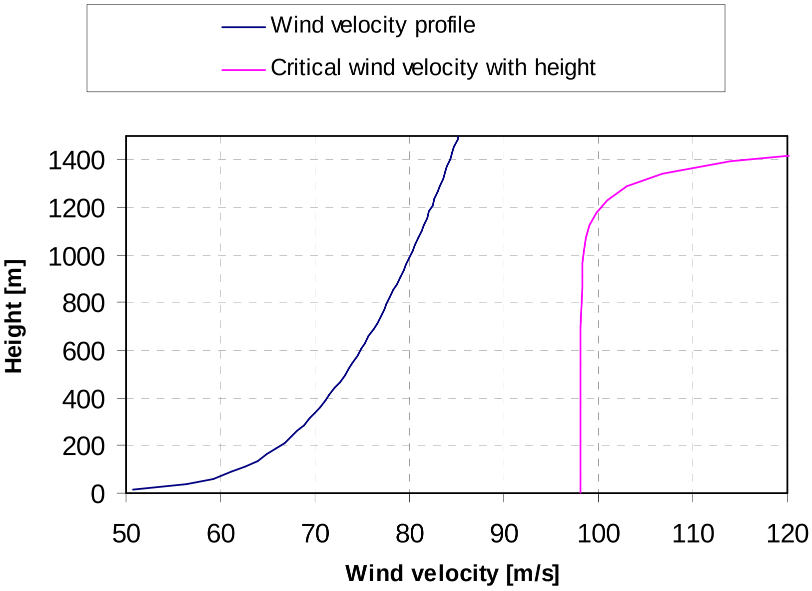


Figure G-3. Proximity of wind velocity profile to critical velocities – reference case.

## G2.2 Wind velocity extrapolation model

The energy yield and capital cost remain unchanged by this theoretical investigation.

Structural performance

The buckling analysis yields a first global buckling value of $\lambda_1 = 2.69$. The decrease in buckling factor is due to the decrease in wind load. Buckling remains localised to the upper regions of the shell. The free vibrations are the same as for the reference case. Lock-in behaviour is not a threat to structural integrity. The calculated values for the along wind gust factor, *G*, follows in Table G-2:

Table G-2. Calculated values for the along wind base overturning moment of the wind velocity extrapolation model.

| Parameter | Value |
|---|---:|
| Height of building, h [m] | 1,500 |
| Horizontal width of structure, b [m] | 160 |
| Roughness length, $z_0$ [m] | 0.02 |
| Longitudinal turbulence intensity, $I_u$, at height h | 0.0891 |
| Roughness factor, r | 0.1782 |
| Peak factor for upwind velocity fluctuation, $g_v$ | 3.7 |
| Effective turbulence length scale, $L_h$ [m] | 3,499.6 |
| Background factor, B | 0.278 |
| Second order effects of turbulence intensity, w | 0.087 |
| Background response | 1.38 |
| First along-wind global free vibration mode | 0.135 |
| Peak factor resonant part of response, $g_f$ | 3.517 |
| Hourly mean wind speed at height h, $V_{h,mean}$ [m/s] | 51.20 |
| Size factor for spatial correlation, S | 0.025 |
| Effective reduced frequency, N | 9.228 |
| Spectrum of turbulence in wind stream, E | 0.105 |
| Structural damping capacity given as fraction of critical damping, $\varsigma$ | 0.0143 |
| **Gust factor, G** | **1.4635** |
| Mean base overturning moment [N.m] | 1.65e+11 |
| **Design peak base overturning moment [N.m]** | **2.42e+11** |

### G2.3 Wind direction variations over chimney height

Not investigated further due to resource constraints and inadequate data (see Appendix F) for wind velocity and directional change with height increase.

### G2.4 Applicability of prescribed critical buckling factor to the SCPP chimney

Not investigated further due to resource constraints.

### G2.5 Cross wind force spectrum

The energy yield and capital cost remain unchanged.

Structural performance

The across wind moment is only applicable to across wind excitation. Assuming that the across wind response is significant, a decrease in the cross wind force spectral value has positive implications on the structural response. Table G-3 depicts the potential impact on the previous case where the chimney height was increased to 1,720 meter (note that adverse across wind frequency response is not excited in the reference case; hence the focus here on the 1,720 meter tall chimney). The spectral value corresponding to the normalised velocity of 4.32 is assumed to be half (this is an arbitrary choice merely to determine system sensitivity to this parameter) (refer to section G1.20 – it was 0.002 and is reduced to 0.001) of what it is for the 1,720 meter chimney:

A decrease of 50% from a cross wind base overturning moment of 9.96e+11 N.m to 6.64e+11 N.m is brought about.

### G2.6 Flaring chimney exit geometry

Energy yield

The increased chimney height concept yields 313.881 GWh/y, an increase of 2.90% on the reference system.

Table G-3. Calculated values for the across wind base overturning moment for cross wind force investigation.

| Parameter | Value |
|---|---|
| Fundamental mode frequency in cross wind direction, $n_c$ [Hz] | 0.094 |
| Peak factor, $g_f$ | 3.411 |
| Width of structure, b [m] | 160 |
| Height of structure, h [m] | 1,720 |
| Hourly mean dynamic wind pressure [Pa] | 2,033.66 |
| Mode shape power exponent, k | 2.4 |
| Hourly mean wind speed, $U_{\text{design hourly mean, h}}$ [m/s] | 66.65 |
| Ratio $U_{\text{design hourly mean, h}} /(n_c \cdot b)$ | 4.46 |
| Cross wind force spectrum coefficient, $C_{fs}$ | 0.001 |
| Structural damping capacity given as fraction of critical damping, $\varsigma$ | 0.0143 |
| **Design across peak base overturning moment [N.m]** | **7.05e+11** |
| **Across resonance peak factor on base overturning moment** | **1.9483** |

Capital cost

The cost model configuration is intuitively adapted only for the flaring volume: R250/m$^3$ is added to the reinforcement quantity in order to resist tensile stresses caused by the flaring geometry. Labour costs are increased by R1,000/m$^3$ and supervision cost by R1,500/m$^3$. The cost of the flaring chimney increases with 0.25% from the reference case value, from R 27.70Bn to R27.77Bn. Costs are reported in Table G-4.

A LEC of R8.422/kWh is calculated.

Table G-4. Cost breakdown of flaring SCPP chimney.

| | Volume [m$^3$] | Unit cost [R/m$^3$] | Cost |
|---|---|---|---|
| **Chimney** | 615,661 | 8,500 (11,250 for flaring) | R 5,012,117,183 |
| **Fins** | 2 609,641 | 8,500 | R 22,181,949,017 |
| **Foundation** | 162,000 | 4,600 | R 557,280,000 |
| **Circumferential stiffeners** | 1,657 | 14,500 | R 20,229,420 |
| | | | R 27,771,575,619 |

Structural performance

The buckling modes are significantly lower than for the reference case. The first global buckling value is $\lambda_1 = 0.68$. The first modes portray *more* localised shell buckling in the flaring part of the shell showing that the flaring geometry is vulnerable to buckling behaviour.

The free vibration analysis yields the first global free vibration frequency of $f_{1,\text{global}}$ = 0.132 Hz. No second global free vibration modes are present in the smaller than 0.2 Hz spectrum. Some more localised ovallising modes are present at $f_{1,\text{local}}$ = 0.124, $f_{2,\text{local}}$ = 0.191 and $f_{3,\text{local}}$ = 0.228 Hz. The slenderness resulted in a lower global free vibration frequency.

The flaring geometrical change is located in the chimney base. For this study it is assumed that the dynamic gust peak method may be used but future investigations should adapt the method for this geometry.

The calculations for the along wind gust factor, *G*, follows in Table G-5.

### G2.7 Chimney inner surface friction

Not investigated further due to insignificant contribution of smoother surface (less friction) on the energy yield (refer to section 7.1.6).

### G2.8 Circumferential stiffener concept

Energy yield

The various concepts have varying impact on the energy yield. An indication is provided in section 7.2.7 with a description of the impact of circumferential stiffener shape on the energy losses. The influence of varying concepts on the energy yield can be described on demand to determine its deviation from the reference circumferential stiffener pressure loss coefficient of 0.01 (see Appendix E).

In the case where the 36 beam circumferential stiffeners are deployed, the circumferential stiffener pressure coefficient is assumed (arbitrary choice in order to determine the sensitivity of the system to less stiffeners) to be half of that of the reference case, at 0.005. The subsequent energy yield increases the reference value by 0.16% to 305.54 GWh/y. The across wind excitation does not pose a threat to structural integrity – Figure G-4.

Table G-5. Calculated values for the along wind base overturning moment of the flaring geometry model.

| Parameter | Value |
|---|---:|
| Height of building, h [m] | 1,500 |
| Horizontal width of structure, b [m] | 160 |
| Roughness length, $z_0$ [m] | 0.02 |
| Longitudinal turbulence intensity, $I_u$, at height h | 0.0891 |
| Roughness factor, r | 0.1782 |
| Peak factor for upwind velocity fluctuation, $g_v$ | 3.7 |
| Effective turbulence length scale, $L_h$ [m] | 3,499.64 |
| Background factor, B | 0.278 |
| Second order effects of turbulence intensity, w | 0.087 |
| Background response | 1.38 |
| First along-wind global free vibration mode | 0.132 |
| Peak factor resonant part of response, $g_f$ | 3.511 |
| Hourly mean wind speed at height h, $V_{h,mean}$ [m/s] | 65.03 |
| Size factor for spatial correlation, S | 0.037 |
| Effective reduced frequency, N | 7.104 |
| Spectrum of turbulence in wind stream, E | 0.123 |
| Structural damping capacity given as fraction of critical damping, $\varsigma$ | 0.0143 |
| **Gust factor, G** | **1.5181** |
| Mean base overturning moment [N.m] | 2.63e+11 |
| **Design peak base overturning moment [N.m]** | **4.00e+11** |

Capital cost

The cost component of the reference case circumferential stiffeners is small, at 0.069% (circumferential stiffener cost divided by total chimney system cost – refer to Table G-1). From a cost perspective the prospect of implementing circumferential stiffeners is attractive. An optimisation between cost and concept and number of circumferential stiffeners, and its impact on energy yield and structural performance should be performed at a pre-feasibility phase.

For the geometry approximation the cost model follows in Table G-6. A LEC of R8.631/kWh is calculated.

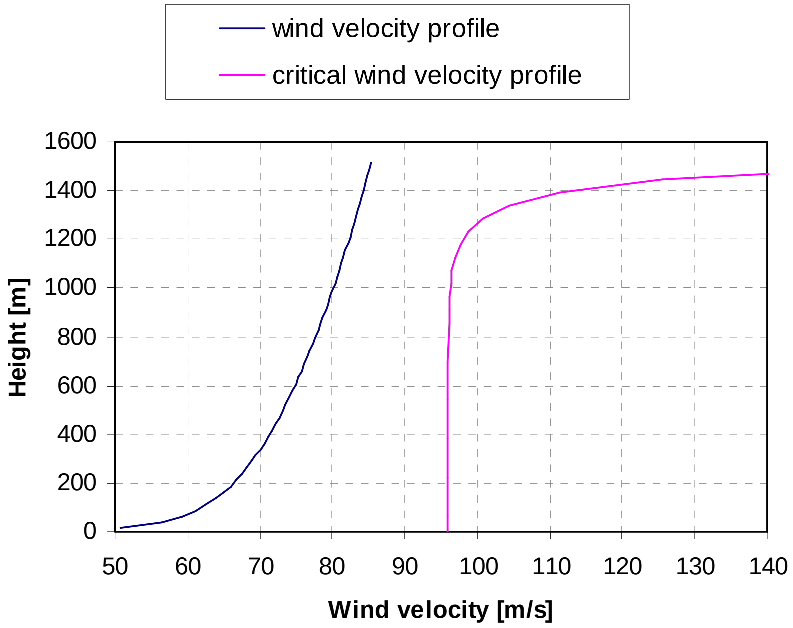


Figure G-4. Proximity of wind velocity profile to critical velocities – flaring chimney.

Table G-6. Cost breakdown of circumferential stiffener concept model.

| | Volume [m$^3$] | Unit cost [R/m$^3$] | Cost |
|---|---|---|---|
| **Chimney** | 581,635 | 8,500 | R 4,943,901,288 |
| **Fins** | 2,609,641 | 8,500 | R 22,181,949,017 |
| **Foundation** | 129,600 | 4,600 | R 557,280,000 |
| **Circumferential stiffeners** | 1,326 | 14,500 | R 9,752,413 |
| | | | R 27,692,882,717 |

Structural performance

Buckling factors are lower than for the reference case, with the first global buckling value of $\lambda_1$ = 1.18 emphasising the great impact the circumferential stiffeners have to mitigate buckling modes.

The first global free vibration frequency remains at $f_{1,\text{global}}$ = 0.135 Hz. No second global free vibration modes are present in the smaller than 0.2 Hz spectrum. The localised ovallising modes, however, are present at much lower frequencies: $f_{1,\text{local}}$ = 0.075, $f_{2,\text{local}}$ = 0.116, $f_{3,\text{local}}$ = 0.175 and $f_{4,\text{local}}$ = 0.2 Hz.

The dynamic response is the same as for the reference case.

### G2.9 Material elasticity modulus

The impact of higher concrete elasticity modulus (60 GPa) on the chimney performance is investigated.

The energy yield remains unchanged.

Capital cost

Quantitative data on the increase in costs due to an increase in concrete elasticity modulus was not available. A value is estimated in order to direct the attention of the decision maker to the presumably high costs incurred with this technology. The reference concrete material cost is increased by four times to a value of R4,000/m$^3$. The basis of these estimations is unpublished values for increased costs of higher strength concretes (as used in the structural laboratories of the US-ISE); costs of these high-strength concretes typically increase by four times). Labour and plant costs are increased by 50%. The consequential cost model is presented below. The cost results are portrayed in Table G-7. A LEC of R9.183/kWh is calculated.

Table G-7. Material elasticity modulus model cost breakdown.

| | Volume [m$^3$] | Unit cost [R/m$^3$] | Cost |
|---|---|---|---|
| **Chimney** | 581,635 | 12,000 | R 6,979,625,348 |
| **Fins** | 2,609,641 | 8,500 | R 22,181,949,017 |
| **Foundation** | 129,600 | 4,600 | R 596,160,000 |
| **Circumferential stiffeners** | 1,326 | 14,500 | R 19,223,581 |
| | | | R 29,738,077,945 |

Structural performance

The buckling analysis yields a first global buckling value of $\lambda_1 = 3.26$ that is significantly closer to that of the reference case. It remains localised to the upper regions of the shell.

The free vibration analysis yields the first global free vibration frequency of $f_{1,\mathrm{global}}$ = 0.187 Hz. No second global free vibration modes are present in the smaller than 0.2 Hz spectrum. Some more localised ovallising modes are present at $f_{1,\mathrm{local}}$ = 0.183 and $f_{2,\mathrm{local}}$ = 0.317 Hz.

The high elasticity modulus has a clear advantageous impact on structural performance.

The calculations for the along wind gust factor, *G*, follows in Table G-8:

The across wind moment is not a threat to structural integrity.

Table G-8. Material elasticity modulus model along wind base overturning moment.

| **Parameter** | **Value** |
|---|---:|
| Height of building, h [m] | 1,500 |
| Horizontal width of structure, b [m] | 160 |
| Roughness length, $z_0$ [m] | 0.02 |
| Longitudinal turbulence intensity, $I_u$, at height h | 0.0891 |
| Roughness factor, r | 0.1782 |
| Peak factor for upwind velocity fluctuation, $g_v$ | 3.7 |
| Effective turbulence length scale, $L_h$ [m] | 3,499.6 |
| Background factor, B | 0.278 |
| Second order effects of turbulence intensity, w | 0.087 |
| Background response | 1.38 |
| First along-wind global free vibration mode | 0.187 |
| Peak factor resonant part of response, $g_f$ | 3.609 |
| Hourly mean wind speed at height h, $V_{h,mean}$ [m/s] | 65.03 |
| Size factor for spatial correlation, S | 0.022 |
| Effective reduced frequency, N | 10.363 |
| Spectrum of turbulence in wind stream, E | 0.099 |
| Structural damping capacity given as fraction of critical damping, $\varsigma$ | 0.0143 |
| **Gust factor, G** | **1.4532** |
| Mean base overturning moment [N.m] | 2.69e+11 |
| **Design peak base overturning moment [N.m]** | **3.90e+11** |

## G2.10 Material density

The impact of lower density reinforced concrete on the chimney performance is investigated. A density of 2,000 kg/m$^3$ is chosen (refer to section 7.1.8 for the validation of this value).

The energy yield remains unchanged.

Capital cost

Data was not available within resources allocated to quantify the changes in costs due to an increase or decrease in concrete density. The cost is therefore assumed to stay constant at R27.70Bn bearing in mind that lower density material available on site may decrease costs. A lower limit LEC of R8.648/kWh is assumed.

Structural performance

The buckling analysis yields a first global buckling value of $\lambda_1 = 1.62$ that is close to that of the reference case. It remains localised to the upper regions of the shell.

The free vibration analysis yields the first global free vibration frequency of $f_{1,\text{global}} = 0.148$ Hz. No second global free vibration modes are present in the smaller than 0.2 Hz spectrum. Some more localised ovallising modes are present at $f_{1,\text{local}} = 0.142$ and $f_{2,\text{local}} = 0.246$ Hz. The higher first global free vibration frequency is due to lower mass concentration in the upper parts of the chimney.

The calculations for the along wind gust factor, *G*, follows in Table G-9.

The across wind moment is not a threat to structural integrity.

Table G-9. Calculated values for the along wind base overturning moment of the material density model.

| Parameter | Value |
|---|---:|
| Height of building, h [m] | 1,500 |
| Horizontal width of structure, b [m] | 160 |
| Roughness length, $z_0$ [m] | 0.02 |
| Longitudinal turbulence intensity, $I_u$, at height h | 0.0891 |
| Roughness factor, r | 0.1782 |
| Peak factor for upwind velocity fluctuation, $g_v$ | 3.7 |
| Effective turbulence length scale, $L_h$ [m] | 3,499.6 |
| Background factor, B | 0.278 |
| Second order effects of turbulence intensity, w | 0.087 |
| Background response | 1.38 |
| First along-wind global free vibration mode | 0.148 |
| Peak factor resonant part of response, $g_f$ | 3.543 |
| Hourly mean wind speed at height h, $V_{h,mean}$ [m/s] | 65.03 |
| Size factor for spatial correlation, S | 0.031 |
| Effective reduced frequency, N | 7.965 |
| Spectrum of turbulence in wind stream, E | 0.115 |

| | |
|---|---|
| Structural damping capacity given as fraction of critical damping, ς | 0.0143 |
| **Gust factor, G** | **1.4933** |
| Mean base overturning moment [N.m] | 2.69e+11 |
| **Design peak base overturning moment [N.m]** | **4.02e+11** |

### G2.11 Internal damping

The reference damping coefficient of the reinforced concrete is 0.0143. The impact of change in this coefficient on the system is investigated; a critical damping factor of 0.091 is assumed (refer to section 7.1.8 for the validation of this choice).

The energy yield remains unchanged.

Capital cost

Data was not available within resources allocated to quantify the changes in costs due to an increase or decrease in concrete internal damping. However, higher damping presumably will incur higher costs. The reference cost is therefore assumed to be a lower limit at R27.70Bn. A lower limit LEC of R8.648/kWh is assumed.

Structural performance

The buckling and free vibration behaviour is identical to that of the reference case. The calculations for the along wind gust factor, *G*, follows in Table G-10.

The across wind moment is not a threat to structural integrity.

Table G-10. Calculated values for the along wind base overturning moment of the material internal damping model.

| Parameter | Value |
|---|---|
| Height of building, h [m] | 1,500 |
| Horizontal width of structure, b [m] | 160 |
| Roughness length, $z_0$ [m] | 0.02 |
| Longitudinal turbulence intensity, $I_u$, at height h | 0.0891 |
| Roughness factor, r | 0.1782 |
| Peak factor for upwind velocity fluctuation, $g_v$ | 3.7 |
| Effective turbulence length scale, $L_h$ [m] | 3,499.6 |
| Background factor, B | 0.278 |

| | |
|---|---|
| Second order effects of turbulence intensity, w | 0.087 |
| Background response | 1.38 |
| First along-wind global free vibration mode | 0.135 |
| Peak factor resonant part of response, $g_f$ | 3.517 |
| Hourly mean wind speed at height h, $V_{h,mean}$ [m/s] | 65.03 |
| Size factor for spatial correlation, S | 0.036 |
| Effective reduced frequency, N | 7.265 |
| Spectrum of turbulence in wind stream, E | 0.121 |
| Structural damping capacity given as fraction of critical damping, $\varsigma$ | 0.0191 |
| **Gust factor, G** | **1.4826** |
| Mean base overturning moment [N.m] | 2.69e+11 |
| **Design peak base overturning moment [N.m]** | **3.99e+11** |

### G2.12 Cable based stabilisation

The accurate modeling of cable-stayed chimney behaviour remains to be investigated. The robust model produced a first global frequency of 0.2547 Hz. The applicability of analytical frequency response methods needs to be determined.

### G2.13 Parabolic hyperboloid geometry

Energy yield

The complexity of the geometry can not readily be incorporated in the thermo-flow simulation model. The reference case energy yield is considered to be a *lower limit* based on the following:

- The more gradual gradient from horisontal to vertical flow of the hyperboloid shape could constitute a decrease in associated losses;
- The larger base diameter increases the perimeter for utilisation as support; and
- Through-flow area could also constitute smaller losses due to changes in through-flow and flow direction area.

Capital cost

An increase in reinforcement amount is incorporated in the cost model by changing the reinforcement cost from R1,000 to R1,200 per cubic meter. The labour cost absorbs all increases in construction cost due to the more complex geometry by increasing from

R2,000 to R2,500 per cubic meter. The cost of the hyperboloid geometry chimney is significantly less than that of the fin-stiffened structure, with a decrease of more than three times from R 27.70Bn to R9.10Bn. The cost breakdown follows in Table G-11. An upper limit LEC of R3.756/kWh is calculated.

Table G-11. Parabolic hyperboloid geometry model cost breakdown.

| | **Volume [m$^3$]** | **Unit cost [R/m$^3$]** | **Cost** |
|---|---|---|---|
| **Chimney** | 865,750 | 9,200 | R 7,964,900,000 |
| **Columns** | 59,417 | 9,200 | R 546,639,911 |
| **Foundation** | 129,600 | 4,300 | R 557,280,000 |
| **Circumferential stiffeners** | 1,326 | 14,500 | R 19,223,581 |
| | | | R 9,088,043,492 |

Structural performance

The buckling analysis yields a first global buckling value of $\lambda_1 = 1.63$. This value is the same as for the reference case because the buckling is not of the cantilever type, but is localised to the upper regions of the shell, presumably due to the relatively thin wall thickness.

The free vibration analysis yields the first global free vibration frequency for $f_{1,\text{global}} = 0.115$ Hz. No second global free vibration modes are present in the smaller than 0.2 Hz spectrum. Some more localised ovallising modes are present at $f_{1,\text{local}} = 0.128$ and $f_{2,\text{local}} = 0.224$ Hz. The hyperboloid shape weakened the chimney against global vibration.

The geometrical change is located in the chimney base. For this study it is assumed that the frequency response method may be used but in future more detailed investigations should adapt the method for this geometry.

The calculations for the along wind gust factor, $G$, follows in Table G-12.

Note that although the base of the chimney is 480 meter wide and not only 160 meter, the 160 meter value is used as a width parameter. The yielded gust factor must, from this perspective, be considered as an *upper limit*.

The across wind moment is not a threat to structural integrity, although close to the critical velocity – Figure G-5.

Table G-12. Calculated values for the along wind base overturning moment of the parabolic hyperboloid geometry model.

| **Parameter** | **Value** |
|---|---|
| Height of building, h [m] | 1,500 |
| Horizontal width of structure, b [m] | 160+ |
| Roughness length, $z_0$ [m] | 0.02 |
| Longitudinal turbulence intensity, $I_u$, at height h | 0.0891 |
| Roughness factor, r | 0.1782 |
| Peak factor for upwind velocity fluctuation, $g_v$ | 3.7 |
| Effective turbulence length scale, $L_h$ [m] | 3,499.6 |
| Background factor, B | 0.278 |
| Second order effects of turbulence intensity, w | 0.087 |
| Background response | 1.38 |
| First along-wind global free vibration mode | 0.115 |
| Peak factor resonant part of response, $g_f$ | 3.472 |
| Hourly mean wind speed at height h, $V_{h,mean}$ [m/s] | 65.03 |
| Size factor for spatial correlation, S | 0.046 |
| Effective reduced frequency, N | 6.189 |
| Spectrum of turbulence in wind stream, E | 0.134 |
| Structural damping capacity given as fraction of critical damping, $\varsigma$ | 0.0143 |
| **Gust factor, G** | **1.553** |
| Mean base overturning moment [N.m] | 2.69e+11 |
| **Design peak base overturning moment [N.m]** | **4.17e+11** |

## G2.14 Chimney diameter

Energy yield

The concept with increased diameter yields 317.75 GWh/y. This is an increase of 4.10%.

Capital cost

An increase in reinforcement amount for the chimney shell is incorporated in the cost model to accommodate for higher circumferential moments by changing the reinforcement cost from R1,000 to R1,200 per cubic meter. Foundation volume is expanded by 5% in accordance with the chimney and fin weight increase. The cost of the

200 meter diameter chimney increases with 2.3% from R 27.70Bn to R28.96Bn. The cost breakdown follows in Table G-13. A LEC of R8.619/kWh is calculated.

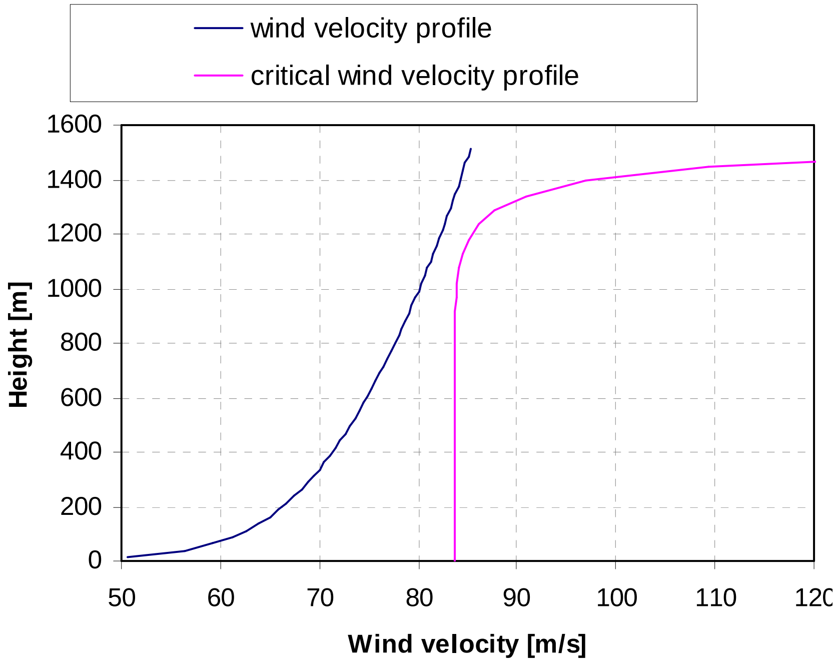


Figure G-5. Proximity of wind velocity profile to critical velocities – parabolic hyperboloid geometry model.

Table G-13. Increased chimney diameter model cost breakdown.

| | Volume [$m^3$] | Unit cost [R/$m^3$] | Cost |
|---|---|---|---|
| **Chimney** | 700,117 | 8,700 | R 6,163,991,220 |
| **Fins** | 2,609,641 | 8,500 | R 22,181,949,017 |
| **Foundation** | 162,000 | 4,600 | R 588,240,000 |
| **Circumferential stiffeners** | 1,657 | 14,500 | R 24,028,041 |
| | | | R 28,958,208,278 |

Structural performance

The buckling analysis yields a first global buckling value of $\lambda_1$ = 1.11. The decrease in buckling factor is due to the decrease in circumferential stiffness. It remains localised to the upper regions of the shell.

The free vibration analysis yields the first global free vibration frequency for $f_{1,\text{global}}$ = 0.163 Hz. No second global free vibration modes are present in the smaller than 0.2 Hz spectrum. Some more localised ovallising modes are present at $f_{1,\text{local}}$ = 0.112, $f_{2,\text{local}}$ = 0.181 and $f_{3,\text{local}}$ = 0.252 Hz. The larger diameter and, hence, cross sectional resistance against global bending, stiffened the chimney against global vibration.

The calculations for the along wind gust factor, *G*, follows in Table G-14:

Table G-14. Calculated values for the along wind base overturning moment of the increased chimney diameter model.

| **Parameter** | **Value** |
|---|---:|
| Height of building, h [m] | 1,500 |
| Horizontal width of structure, b [m] | 200 |
| Roughness length, $z_0$ [m] | 0.02 |
| Longitudinal turbulence intensity, $I_u$, at height h | 0.0891 |
| Roughness factor, r | 0.1782 |
| Peak factor for upwind velocity fluctuation, $g_v$ | 3.7 |
| Effective turbulence length scale, $L_h$ [m] | 3,499.6 |
| Background factor, B | 0.277 |
| Second order effects of turbulence intensity, w | 0.087 |
| Background response | 1.38 |
| First along-wind global free vibration mode | 0.163 |
| Peak factor resonant part of response, $g_f$ | 3.571 |
| Hourly mean wind speed at height h, $V_{h,\text{mean}}$ [m/s] | 65.03 |
| Size factor for spatial correlation, S | 0.024 |
| Effective reduced frequency, N | 8.772 |
| Spectrum of turbulence in wind stream, E | 0.108 |
| Structural damping capacity given as fraction of critical damping, $\varsigma$ | 0.0143 |
| **Gust factor, G** | **1.4626** |
| Mean base overturning moment [N.m] | 3.38e+11 |
| **Design peak base overturning moment [N.m]** | **4.94e+11** |

The across wind moment is not a threat to structural integrity.

## G2.15 Number of circumferential stiffeners

Energy yield

The added flow resistance brought about by the five additional braces has a slight impact on the energy yield: the energy yield decreases by 0.3% to approximately 304.12 GWh/y.

Capital cost

The cost model configuration remains the same as for the reference case. The cost of the chimney increases by approximately 0.05% from R 27.70Bn to R27.72Bn. Table G-15 reports the cost breakdown. A LEC of R8.678/kWh is calculated.

Table G-15. Number of circumferential stiffeners model cost breakdown.

| | Volume [m$^3$] | Unit cost [R/m$^3$] | Cost |
|---|---|---|---|
| **Chimney** | 581,635 | 8,500 | R 4,943,901,288 |
| **Fins** | 2,609,641 | 8,500 | R 22,181,949,017 |
| **Foundation** | 129,600 | 4,300 | R 557,280,000 |
| **Circumferential stiffeners** | 1,326 | 14,500 | R 35,008,861 |
| | | | R 27,718,139,165 |

Structural performance

Buckling factors are higher than for the reference case, the first global buckling value of $\lambda_1$ = 2.70, displaying semi-localised buckling in the upper region of the chimney. This indicates the influence of circumferential stiffeners to mitigate buckling modes.

The first global free vibration frequency for $f_{1,\mathrm{global}}$ = 0.135 Hz. No second global free vibration modes are present in the smaller than 0.2 Hz spectrum. Some more localised ovallising modes are present at $f_{1,\mathrm{local}}$ = 0.131 and $f_{2,\mathrm{local}}$ = 0.231 Hz.

The along wind gust factor, *G*, is the same as for the reference case. Across wind resonance does not pose a threat to structural integrity.

### G2.16 Wall thickness re-configuration

It is assumed that the wall thickness changes do not impact energy yield with the inner diameter remaining constant over height.

Capital cost

The cost model configuration remains the same as for the reference case. The foundation costs are decreased in accordance with chimney volume decrease. The cost of the chimney decreases by approximately 5.6% from R 27.70Bn to R26.21Bn. Table G-16 reports the cost breakdown. A LEC of R8.284/kWh is calculated.

Table G-16. Re-configured wall thickness model cost breakdown.

| | Volume [$m^3$] | Unit cost [$R/m^3$] | Cost |
|---|---|---|---|
| **Chimney** | 410,901 | 8,500 | R 3,492,658,667 |
| **Fins** | 2,609,641 | 8,500 | R 22,181,949,017 |
| **Foundation** | 162,000 | 4,300 | R 527,465,241 |
| **Circumferential stiffeners** | 1,657 | 14,500 | R 19,223,581 |
| | | | R 26,221,296,505 |

Structural performance

The increased wall thickness in the upper regions of the chimney has a significant effect on the buckling behaviour. Buckling factors are significantly higher than for the reference case, the first global buckling value being $\lambda_1$ = 3.74. The location of the buckling is in the lower regions of the chimney shell, see Figure G-6. It is concluded that the increased wall thickness has a significant effect in mitigating the semi-localised buckling modes in the upper parts of the shell.

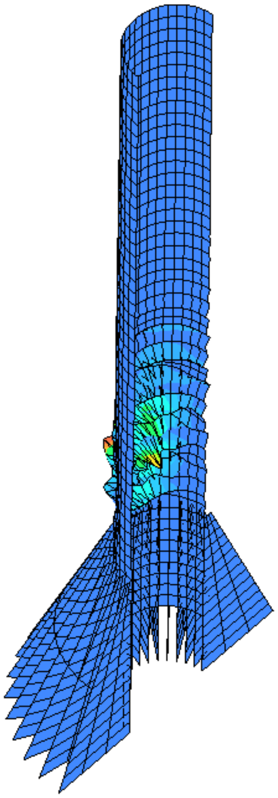


Figure G-6. Shell buckling in the lower regions of the chimney with re-configured wall thickness.

The increased wall thickness in the upper regions concentrates more mass in these parts of the structure which predicts lower global natural frequencies: the first global free vibration frequency of $f_{1,\mathrm{global}}$ = 0.097 Hz. No second global free vibration modes are present in the smaller than 0.2 Hz spectrum. Some more localised ovallising modes are present at $f_{1,\mathrm{local}}$ = 0.129 and $f_{2,\mathrm{local}}$ = 0.237 Hz.

The calculations for the along wind gust factor, *G*, follows in Table G-17:

Table G-17. Calculated values for the along wind base overturning moment of the re-configured wall thickness model.

| **Parameter** | **Value** |
|---|---:|
| Height of building, h [m] | 1,500 |
| Horizontal width of structure, b [m] | 160 |
| Roughness length, $z_0$ [m] | 0.02 |
| Longitudinal turbulence intensity, $I_u$, at height h | 0.0891 |
| Roughness factor, r | 0.1782 |
| Peak factor for upwind velocity fluctuation, $g_v$ | 3.7 |
| Effective turbulence length scale, $L_h$ [m] | 3,499.64 |
| Background factor, B | 0.278 |
| Second order effects of turbulence intensity, w | 0.087 |
| Background response | 1.38 |
| First along-wind global free vibration mode | 0.097 |
| Peak factor resonant part of response, $g_f$ | 3.422 |
| Hourly mean wind speed at height h, $V_{h,mean}$ [m/s] | 65.03 |
| Size factor for spatial correlation, S | 0.058 |
| Effective reduced frequency, N | 5.225 |
| Spectrum of turbulence in wind stream, E | 0.147 |
| Structural damping capacity given as fraction of critical damping, $\varsigma$ | 0.0143 |
| **Gust factor, G** | **1.6034** |
| Mean base overturning moment [N.m] | 2.69e+11 |
| **Design peak base overturning moment [N.m]** | **4.31e+11** |

Figure G-6 depicts the critical wind velocities (lock-in) as well inside the peak velocity profile over most of the structural height. The across wind resonance could pose a threat to structural integrity. The across wind overturning moment is calculated in Table G-18.

Figure G-6. Proximity of wind velocity profile to critical velocities – model with re-configured wall thickness.

Table G-18. Calculated values for the across wind base overturning moment of the re-configured wall thickness model.

| Parameter | Value |
|---|---|
| Fundamental mode frequency in cross wind direction, $n_c$ [Hz] | 0.097 |
| Peak factor, $g_f$ | 3.422 |
| Width of structure, b [m] | 160 |
| Height of structure, h [m] | 1,500 |
| Hourly mean dynamic wind pressure | 1,980.06 |
| Mode shape power exponent, k | 2.4 |
| Hourly mean wind speed, $U_{\text{design hourly mean, h}}$ [m/s] | 65.03 |
| Ratio $U_{\text{design hourly mean, h}}$ /($n_c \cdot b$) | 4.19 |
| Cross wind force spectrum coefficient, $C_{fs}$ | 0.00175 |
| Structural damping capacity given as fraction of critical damping, $\varsigma$ | 0.0143 |
| **Design across peak base overturning moment [N.m]** | **7.03e+11** |
| **Across resonance peak factor on base overturning moment** | **2.611** |

### G2.17 External damping devices

This study does not engage the complex field of external damping due to resource constraints, but notes it as a possibly critical measure in mitigating resonant response in the SCPP chimney at little or no additional energy loss and small capital expenditure.

### G2.18 Manipulation of wind-structure interaction: circumferential pressure distribution

Energy yield

The inner volume of the chimney remains the same as for the reference case; hence the energy yield remains unchanged.

Capital cost

A lower limit cost is calculated for an inflated membrane concept generating the Saguaro geometry. This comprises the appropriate area of membrane assumed to cost approximately R100/m$^2$ including material, construction, fastening and inflation. This is based on 45 membrane spikes along the chimney circumference protruding 11.2 meters. Thus, the lower limit cost is estimated at R27.83Bn which represents a 0.47% increase. Table G-19 breaks down the costs. A lower limit LEC of R8.682/kWh is calculated.

Table G-19. Saguaro geometry model modulus model cost breakdown.

| | **Volume [m$^3$]** | **Unit cost [R/m$^3$]** | **Cost** |
|---|---|---|---|
| **Chimney** | 581,635 | 8,500 | R 4,943,901,288 |
| **Fins** | 2,609,641 | 8,500 | R 22,181,949,017 |
| **Foundation** | 129,600 | 4,600 | R 557,280,000 |
| **Circumferential stiffeners** | 1,326 | 14,500 | R 19,223,581 |
| **Inflated membrane** | 1,295,334 m$^2$ | R100/m$^2$ | R 129,553,392 |
| | | | R 27,831,887,277 |

Structural performance

Buckling factors are higher than for the reference case, the first global buckling value of $\lambda_1 = 1.92$, a net improvement with the favourable circumferential pressure distribution, but higher overall load area. Note again that this serves as the lower limit because the

Saguaro geometry does not have any structural capacity in the model analysed. The free vibration frequencies are also assumed to be the same as for the reference case without the structural stiffening.

The calculations for the along wind gust factor, *G*, follows in Table G-20. Although the gust factor is of similar order to that of the reference case, the overturning moment is significantly higher due to the effective increase of the chimney width.

Table G-20. Calculated values for the along wind base overturning moment of the Saguaro geometry model.

| **Parameter** | **Value** |
|---|---:|
| Height of building, h [m] | 1,500 |
| Horizontal width of structure, b [m] | 182.4 |
| Roughness length, $z_0$ [m] | 0.02 |
| Longitudinal turbulence intensity, $I_u$, at height h | 0.0891 |
| Roughness factor, r | 0.1782 |
| Peak factor for upwind velocity fluctuation, $g_v$ | 3.7 |
| Effective turbulence length scale, $L_h$ [m] | 3,499.64 |
| Background factor, B | 0.277 |
| Second order effects of turbulence intensity, w | 0.087 |
| Background response | 1.38 |
| First along-wind global free vibration mode | 0.135 |
| Peak factor resonant part of response, $g_f$ | 3.517 |
| Hourly mean wind speed at height h, $V_{h,mean}$ [m/s] | 65.03 |
| Size factor for spatial correlation, S | 0.033 |
| Effective reduced frequency, N | 7.265 |
| Spectrum of turbulence in wind stream, E | 0.121 |
| Structural damping capacity given as fraction of critical damping, $\varsigma$ | 0.0143 |
| **Gust factor, G** | **1.504** |
| Mean base overturning moment [N.m] | 3.08e+11 |
| **Design peak base overturning moment [N.m]** | **4.64e+11** |

The lock-in range is well outside the peak velocity profile over all of the structural height. Across wind resonance does not pose a threat to structural integrity.

## G2.19 Directional design

An investigation must be performed to determine the feasibility of this design approach with regards to decreasing material volumes (hence, capital cost) while not compromising structural integrity. This prospect is not investigated further due to resource constraints.

## G2.20 Heightened chimney

Energy yield

The increased chimney height concept yields 355.93 GWh/y; an increase of 16.7%.

Capital cost

The cost model configuration remains similar to the reference case model. The cost of the 1,720 meter height chimney increases 1% from R 27.70Bn to R28.07Bn. Table G-21 reports the cost breakdown. A LEC of R7.485/kWh is calculated.

Table G-21. Increase chimney height model cost breakdown.

| | Volume [m$^3$] | Unit cost [R/m$^3$] | Cost |
|---|---|---|---|
| **Chimney** | 615,661 | 8,500 | R 5,233,116,622 |
| **Fins** | 2,609,641 | 8,500 | R 22,181,949,017 |
| **Foundation** | 162,000 | 4,600 | R 589,602,240 |
| **Circumferential stiffeners** | 1,657 | 14,500 | R 22,380,637 |
| | | | R 28,027,048,515 |

Structural performance

The buckling analysis yields a first global buckling value of $\lambda_1 = 1.53$, slightly lower than the value of 1.63 calculated for the reference case. It remains localised to the upper regions of the shell.

The free vibration analysis yields the first global free vibration frequencies for $f_{1,\text{global}} = 0.094$ Hz – the additional slenderness resulting in a lower global free vibration frequency. No second global free vibration modes are present in the smaller than 0.2 Hz spectrum. Some more localised ovallising modes are present at $f_{1,\text{local}} = 0.108$, $f_{2,\text{local}} = 0.193$ and $f_{3,\text{local}} = 0.241$ Hz.

The calculations for the along wind gust factor, *G*, follows in Table G-22.

Table G-22. Calculated values for the along wind base overturning moment of the increased chimney height model.

| Parameter | Value |
|---|---:|
| Height of building, h [m] | 1,720 |
| Horizontal width of structure, b [m] | 160 |
| Roughness length, $z_0$ [m] | 0.02 |
| Longitudinal turbulence intensity, $I_u$, at height h | 0.0880 |
| Roughness factor, r | 0.1760 |
| Peak factor for upwind velocity fluctuation, $g_v$ | 3.7 |
| Effective turbulence length scale, $L_h$ [m] | 3,621.45 |
| Background factor, B | 0.258 |
| Second order effects of turbulence intensity, w | 0.083 |
| Background response | 1.36 |
| First along-wind global free vibration mode | 0.094 |
| Peak factor resonant part of response, $g_f$ | 3.411 |
| Hourly mean wind speed at height h, $V_{h,mean}$ [m/s] | 66.65 |
| Size factor for spatial correlation, S | 0.056 |
| Effective reduced frequency, N | 5.080 |
| Spectrum of turbulence in wind stream, E | 0.149 |
| Structural damping capacity given as fraction of critical damping, $\varsigma$ | 0.0143 |
| **Gust factor, G** | **1.582** |
| Mean base overturning moment [N.m] | 3.62e+11 |
| **Design peak base overturning moment [N.m]** | **5.72e+11** |

The across wind moment is a threat to structural integrity. Figure G-7 depicts the lock-in range well inside the peak velocity profile over most of the structural height.

The across wind moment calculation is determined as formulated earlier and tabulated in Table G-23:

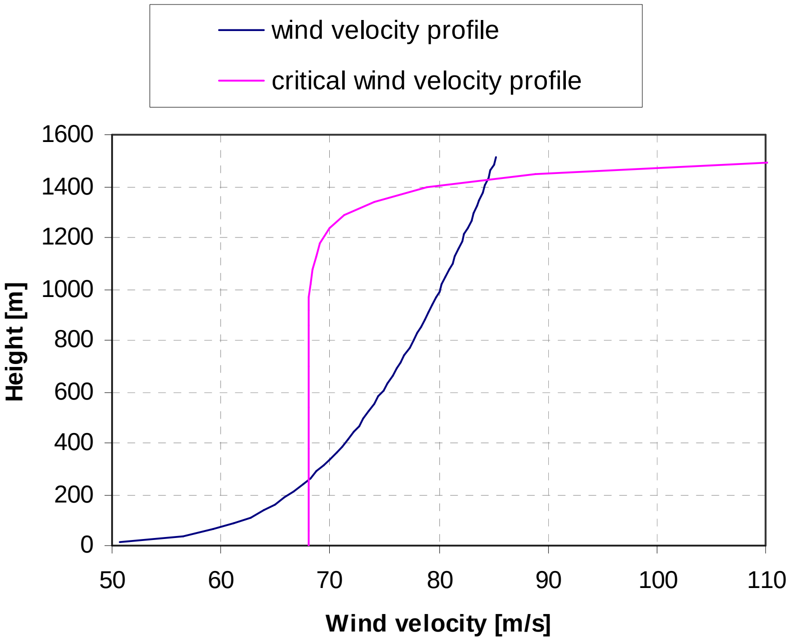


Figure G-7. Proximity of wind velocity profile to critical velocities – increased chimney height.

Table G-23. Calculated values for the across wind base overturning moment of the increased chimney height model.

| Parameter | Value |
|---|---|
| Fundamental mode frequency in cross wind direction, $n_c$ [Hz] | 0.094 |
| Peak factor, $g_f$ | 3.411 |
| Width of structure, b [m] | 160 |
| Height of structure, h [m] | 1,720 |
| Hourly mean dynamic wind pressure | 2,033.66 |
| Mode shape power exponent, k | 2.4 |
| Hourly mean wind speed, $U_{\text{design hourly mean, h}}$ [m/s] | 66.65 |
| Ratio $U_{\text{design hourly mean, h}}/(n_c \cdot b)$ | 4.46 |
| Cross wind force spectrum coefficient, $C_{fs}$ | 0.002 |
| Structural damping capacity given as fraction of critical damping, $\varsigma$ | 0.0143 |
| **Design across peak base overturning moment [N.m]** | **9.97e+11** |
| **Across resonance peak factor on base overturning moment** | **2.755** |

### G2.21 Terrain surface roughness

The energy yield and capital cost remain unchanged.

Structural performance

The buckling analysis yields a higher first global buckling value of $\lambda_1$ = 1.832 due to the lower peak wind velocities.

The free vibration remains the same. The along wind gust factor, *G*, is calculated in Table G-24.

Table G-24. Calculated values for the along wind base overturning moment of the terrain surface roughness model.

| Parameter | Value |
|---|---:|
| Height of building, h [m] | 1,500 |
| Horizontal width of structure, b [m] | 160 |
| Roughness length, $z_0$ [m] | 0.01 |
| Longitudinal turbulence intensity, $I_u$, at height h | 0.0839 |
| Roughness factor, r | 0.1678 |
| Peak factor for upwind velocity fluctuation, $g_v$ | 3.7 |
| Effective turbulence length scale, $L_h$ [m] | 3,499.6 |
| Background factor, B | 0.278 |
| Second order effects of turbulence intensity, w | 0.082 |
| Background response | 1.35 |
| First along-wind global free vibration mode | 0.135 |
| Peak factor resonant part of response, $g_f$ | 3.517 |
| Hourly mean wind speed at height h, $V_{h,mean}$ [m/s] | 62.33 |
| Size factor for spatial correlation, S | 0.034 |
| Effective reduced frequency, N | 7.580 |
| Spectrum of turbulence in wind stream, E | 0.118 |
| Structural damping capacity given as fraction of critical damping, $\varsigma$ | 0.0143 |
| **Gust factor, G** | **1.472** |
| Mean base overturning moment [N.m] | 2.22e+11 |
| **Design peak base overturning moment [N.m]** | **3.26e+11** |

The across wind moment is not a threat to structural integrity.

## G3 Aggregated data

The system performance data is aggregated into Table G-25. Clear blocks indicate when, within the assumptions made and degree of augmentation chosen, the evaluation model delivered a conclusive result. A yellow block indicates lower limit values, a turquoise block indicates an upper limit value and a grey block indicates rough estimation of quantitative data.

The normalised values are reported in Table G-26. Note that the reciprocal values of LEC and dynamic response criteria are presented in order for a “positive” score to imply positive implication for system performance.

Note that the frequency response factors often exceed the ideally required value and in cases has a very adverse impact on the system.

Table G-25. Summary of performance data for all alternatives.

| **Alternative** | **Levelised Electricity Cost** | **Buckling factor** | **Dynamic response factor** |
|---|---:|---:|---:|
| Reference | R 8.65 | 1.63 | 1.513 |
| Wind velocity extrapolation | R 8.65 | 2.69 | 1.464 |
| Flaring chimney exit | R 8.42 | 0.68 | 1.518 |
| Circumferential stiffener concept | R 8.63 | 1.18 | 1.513 |
| Material elasticity modulus | R 9.18 | 3.26 | 1.453 |
| Material density | R 8.65 | 1.62 | 1.493 |
| Internal damping | R 8.65 | 1.63 | 1.483 |
| Parabolic hyperboloid geometry | R 3.76 | 1.63 | 1.553 |
| Chimney diameter | R 8.62 | 1.11 | 1.463 |
| Number of circumferential stiffeners | R 8.68 | 2.70 | 1.513 |
| Wall thickness re-configuration | R 8.28 | 3.74 | 2.611 |
| Saguaro geometry | R 8.68 | 1.92 | 1.504 |
| Heightened chimney | R 7.49 | 1.53 | 2.755 |
| Terrain surface roughness | R 8.65 | 1.83 | 1.472 |
| Radical goal | R 1.00 | 5.00 | 1.500 |

Table G-26. Normalised data for all alternatives.

| Alternative | Normalised | | |
|---|---|---|---|
| | Levelised Electricity Cost | Buckling factor | Dynamic response factor |
| Reference | 0.00 | 0.00 | 0.00 |
| Wind velocity extrapolation | 0.00 | 0.31 | 3.77 |
| Flaring chimney exit | 0.03 | -0.28 | -0.38 |
| Circumferential stiffener concept | 0.00 | -0.13 | 0.00 |
| Material elasticity modulus | -0.07 | 0.48 | 4.62 |
| Material density | 0.00 | 0.00 | 1.54 |
| Internal damping | 0.00 | 0.00 | 2.31 |
| Parabolic hyperboloid geometry | 0.64 | 0.00 | -3.08 |
| Chimney diameter | 0.00 | -0.15 | 3.85 |
| Number of circumferential stiffeners | 0.00 | 0.32 | 0.00 |
| Wall thickness re-configuration | 0.05 | 0.63 | -84.46 |
| Saguaro geometry | 0.00 | 0.09 | 0.69 |
| Heightened chimney | 0.15 | -0.03 | -95.54 |
| Terrain surface roughness | 0.00 | 0.06 | 3.15 |
| Radical goal | 1.00 | 1.00 | 1.00 |

# APPENDIX H

# CRITICAL EVALUATION OF US SCPP R&D

## H1 Cascade of technological trends

### H1.1 Recap of the cascade of technological trends

The cascade of technological trends presented in section 3.6.2 presents a normative pattern for technological development. To recap briefly, technological change occurs through consecutive levels from;

- Level 1: material characteristics (function and structure),
- Level 2: system size, structure and operating principle,
- Level 3: performance
- Level 4: cost decrease and improvement in safety, health and environmental (SHE) impact, and, finally,
- Level 5: the diffusion of technology into the landscape.

### H1.2 US SCPP research cascade levels

The research performed on the SCPP over ten years at the US covered several levels predicted by the cascade as follows, in order of occurrence:

- Thermo dynamics covered
    - the mathematical description of the thermo dynamic performance, i.e. Level 3
    - innovative solutions to improve the operating principle, i.e. Level 2
    - cost decrease, i.e. Level 4
    - market dictated system re-configuration/conceptualisation, i.e. Level 5
- Flow dynamics covered
    - the mathematical description of the flow performance, i.e. Level 3

  - innovative solutions to improve the operating principle, i.e. Level 2
  - cost decrease, i.e. Level 4
- Structural engineering covered
  - material characteristics, i.e. Level 1
  - the structural operating principle and system size, i.e. Level 2
  - structural performance, i.e. Level 3
  - cost decrease and reliability, i.e. Level 4
  - market (cost) dictated technology conceptualisation, i.e. Level 5
- Environmental investigation covered
  - Environmental Impact Assessment, i.e. Level 4
- Economic investigation covered
  - cost model describing all cost inputs on conceptual level, i.e. Level 3

The process of technological development perceived in the SCPP project at the US comprised of the cascade levels in Table H-1. Table H-2 portrays the flow of technology development at the US over the period of its R&D.

Table H-1. US research in terms of technology development cascade levels.

| | **Field** | | | | |
|---|---|---|---|---|---|
| **Date** | **Thermo-dynamics** | **Flow-dynamics** | **Structural** | **Environment** | **Economic** |
| 1997 | 2 | 2 | | | |
| 1998 | 2 | 2 | | | |
| 1999 | 2 | 2 | | | |
| 2000 | 2 | 2/3 | | | |
| 2001 | 2/3 | 2/3 | 1/2/3 | | |
| 2002 | 2/3 | 2/3 | 2/3 | | |
| 2003 | 2/4 | 2/3 | 3 | | |
| 2004 | 3 | 2/3 | 2/3/4 | 4 | |
| 2005 | 2/3 | 2/3 | 2/3/4 | | |
| 2006 | | 2/3 | 2/3/4 | | 4 |
| 2007 | 3/4/5 | | 2/3/4/5 | | |

Table H-2. Involvement in cascade levels over the 10 year US research program.

| Date | **Level 1** | **Level 2** | **Level 3** | **Level 4** | **Level 5** |
|---|---|---|---|---|---|
| 1997 | | 🟨 | | | |
| 1998 | | 🟨 | | | |
| 1999 | | 🟨 | | | |
| 2000 | 🟨 | 🟨 | 🟨 | | |
| 2001 | 🟨 | 🟨 | 🟨 | | |
| 2002 | 🟨 | 🟨 | 🟨 | | |
| 2003 | 🟨 | 🟨 | 🟨 | 🟨 | |
| 2004 | 🟨 | 🟨 | 🟨 | 🟨 | |
| 2005 | 🟨 | 🟨 | 🟨 | 🟨 | |
| 2006 | 🟨 | 🟨 | 🟨 | 🟨 | |
| 2007 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 |

Table H-3. Involvement in cascade levels over the 7 year US-ISE research program.

| Date | **Level 1** | **Level 2** | **Level 3** | **Level 4** | **Level 5** |
|---|---|---|---|---|---|
| 2001 | 🟨 | 🟨 | 🟨 | | |
| 2002 | | 🟨 | 🟨 | | |
| 2003 | | | 🟨 | | |
| 2004 | | 🟨 | 🟨 | 🟨 | |
| 2005 | | 🟨 | 🟨 | 🟨 | |
| 2006 | | 🟨 | 🟨 | 🟨 | |
| 2007 | | 🟨 | 🟨 | 🟨 | 🟨 |

### H1.3 Discussion

The research methodology followed at the US first aimed to describe the operating principles of the SCPP thermo- and flow-dynamical cycles in order to understand the capabilities and limitations of the system before venturing into material, system size, structure, performance and the cost, SHE and diffusion developments.

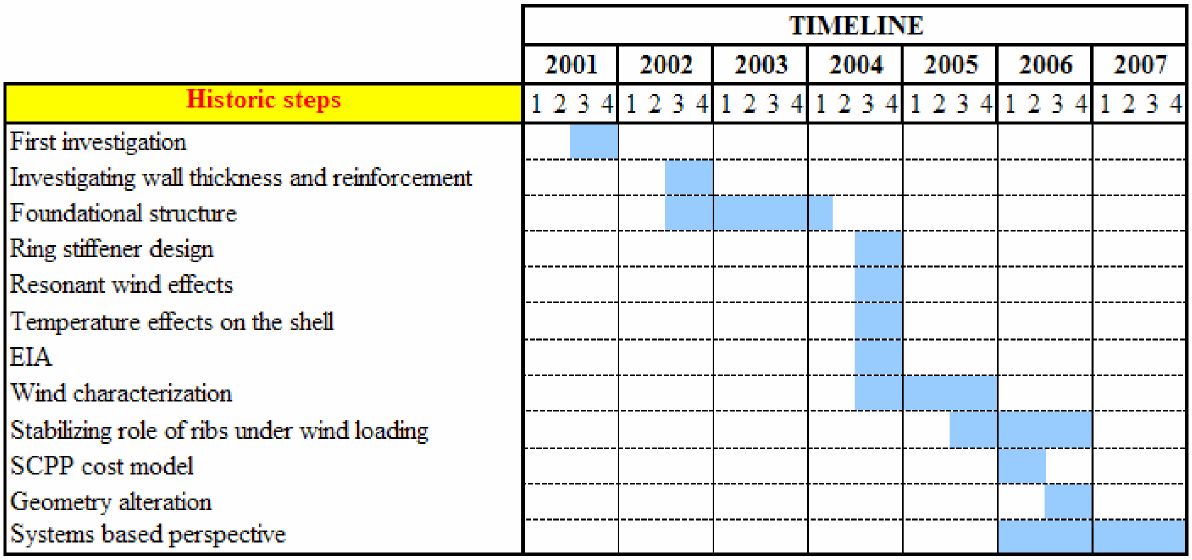
The stepwise venturing into higher cascade level research as the project progresses is noteworthy from Figure H-2. Future research must be directed to focus on the higher cascade levels, thus cost decrease, improvement of safety and environmental impact and market diffusion. This confirms the fact that the thermo- and flow-dynamical fields are at this stage already well described, with the structural field progressively growing toward the same status (Figure H3). Subsequent technological development must focus on the optimisation (performance and cost) and SHE aspects and eventually diffuse the product into the market through developing business plans and addressing specific local and global market needs to draw investors.

Further, the structural R&D was spread out over several cascade levels, mostly Levels 2 to 4. This may indicate the inability to decouple cascade levels in structural research or the definition of research topics without a governing, directing system and technology perspective, covering too wide a scope of subject matter.

## H2 Efficiency of structural SCPP chimney research

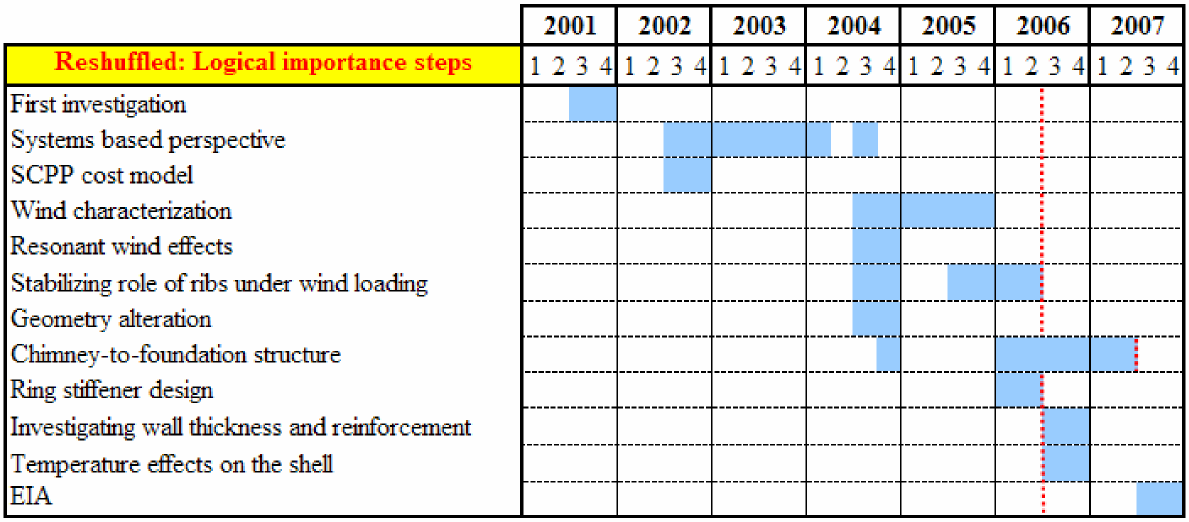
Table H-4 portrays the historic progress of R&D on the SCPP chimney at the US-ISE. Table H-5 depicts how this could be optimised while utilising the same resources, thereby performing early systems based research to identify critical issues in the radical innovation. Resources are allocated to first complete critical issues – the red dashed line indicates the stage when the most critical research topics (as identified without the comprehensive perspective of a systems based investigation) could have been completed (with the exception of the foundation structure).

Table H-4. Historic breakdown of R&D allocation.



| | TIMELINE | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2001 | | | | 2002 | | | | 2003 | | | | 2004 | | | | 2005 | | | | 2006 | | | | 2007 | | | |
| **Historic steps** | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 |
| First investigation | | | 🟦 | 🟦 | | | | | | | | | | | | | | | | | | | | | | | | |
| Investigating wall thickness and reinforcement | | | | | | | 🟦 | 🟦 | | | | | | | | | | | | | | | | | | | | |
| Foundational structure | | | | | | | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | | | | | | | | | | | | | | | |
| Ring stiffener design | | | | | | | | | | | | | | | 🟦 | 🟦 | | | | | | | | | | | | |
| Resonant wind effects | | | | | | | | | | | | | | | 🟦 | 🟦 | | | | | | | | | | | | |
| Temperature effects on the shell | | | | | | | | | | | | | | | 🟦 | 🟦 | | | | | | | | | | | | |
| EIA | | | | | | | | | | | | | | | 🟦 | 🟦 | | | | | | | | | | | | |
| Wind characterization | | | | | | | | | | | | | | | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | | | | | | | | |
| Stabilizing role of ribs under wind loading | | | | | | | | | | | | | | | | | | | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | | | | |
| SCPP cost model | | | | | | | | | | | | | | | | | | | | | 🟦 | 🟦 | | | | | | |
| Geometry alteration | | | | | | | | | | | | | | | | | | | | | | | 🟦 | 🟦 | | | | |
| Systems based perspective | | | | | | | | | | | | | | | | | | | | | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 | 🟦 |

Table H-5. Optimised breakdown of R&D allocation.



| | 2001 | | | | 2002 | | | | 2003 | | | | 2004 | | | | 2005 | | | | 2006 | | | | 2007 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Reshuffled: Logical importance steps** | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 |
| First investigation | | | ■ | ■ | | | | | | | | | | | | | | | | | | | | | | | | |
| Systems based perspective | | | | | | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | ■ | | | | | | | | | | | | | |
| SCPP cost model | | | | | | | ■ | ■ | | | | | | | | | | | | | | | | | | | | |
| Wind characterization | | | | | | | | | | | | | | | ■ | ■ | ■ | ■ | ■ | ■ | | | | | | | | |
| Resonant wind effects | | | | | | | | | | | | | | | ■ | ■ | | | | | | | | | | | | |
| Stabilizing role of ribs under wind loading | | | | | | | | | | | | | | | ■ | ■ | | | ■ | ■ | ■ | ■ | | | | | | |
| Geometry alteration | | | | | | | | | | | | | | | ■ | ■ | | | | | | | | | | | | |
| Chimney-to-foundation structure | | | | | | | | | | | | | | | | ■ | | | | | ■ | ■ | ■ | ■ | ■ | ■ | | |
| Ring stiffener design | | | | | | | | | | | | | | | | | | | | | ■ | ■ | | | | | | |
| Investigating wall thickness and reinforcement | | | | | | | | | | | | | | | | | | | | | | | ■ | ■ | | | | |
| Temperature effects on the shell | | | | | | | | | | | | | | | | | | | | | | | ■ | ■ | | | | |
| EIA | | | | | | | | | | | | | | | | | | | | | | | | | | | ■ | ■ |

# APPENDIX I

# MODEL OF SYNTHESISED TOP TECHNOLOGIES

## I1 Results of the model of synthesised top technologies

Four of the top technologies (section 9.2.2) are incorporated into the first iteration reference case. The results are reported here. The wall thickness re-configuration, as formulated in section 7.1.13, is included in combination with the parabolic hyperboloid geometry (section 7.1.10), the addition of the five additional circumferential stiffeners (section 7.1.12) and the ultra-high strength performance concrete (section 7.1.8) (a modulus of elasticity at 60 GPa was chosen in the latter case).

Energy yield

The only geometrical changes in the synthesised model are the parabolic hyperboloid geometry, the re-configuration of the wall thickness and the addition of circumferential stiffeners. Of these, the parabolic hyperboloid geometry and the stiffeners have an impact on energy yield. The energy yield has a slightly decreased lower limit than that of the parabolic hyperboloid system of section 7.1.10 due to the presence of the additional circumferential stiffeners, at 304.13 GWh/y which is approximately 0.3% lower than that of the reference case.

Capital cost

The concrete material cost is increased by four times to a value of R4,000/m$^3$ (validation of this value was stated in Appendix G2.9). Labour and plant costs are increased by 50%. The capital costs are reduced from R27.70Bn to R8.55Bn resulting in a LEC of R3.627/kWh.

The cost breakdown follows in Table I-1.

Table I-1. Epilogue model cost breakdown.

| | **Volume [m$^3$]** | **Unit cost [R/m$^3$]** | **Cost** |
|---|---|---|---|
| **Chimney** | 604,144 | 12,000 | R 7,249,733,155 |
| **Columns** | 2,609,641 | 12,000 | R 713,008,580 |
| **Foundation** | 129,600 | 4,300 | R 557,280,000 |
| **Circumferential stiffeners** | 1,326 | 14,500 | R 35,008,861 |
| | | | R 8,555,030,595 |

<u>Structural performance</u>

The critical buckling factor surpassed the ‘ideal’ 5.0 mark with a first global buckling mode value of $\lambda_1$ = 5.75, as is portrayed in Figure I-1. The buckling occurs in the lower regions of the chimney shell (The upper regions are now more stable due to application of the mitigating technologies.).

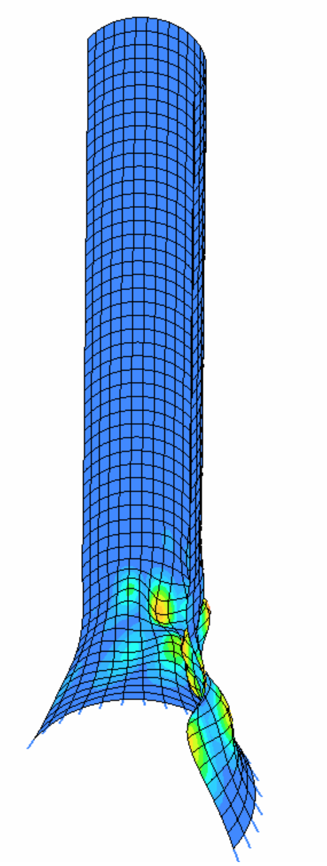


Figure I-1. SCPP chimney updated model first buckling mode.

The free vibration analysis yields the first global free vibration frequencies $f_{1,\mathrm{global}}$ = 0.113 Hz. No second global free vibration modes are present in the smaller than 0.2 Hz spectrum. Some more localised ovallising modes are present at $f_{1,\mathrm{local}}$ = 0.128 and $f_{2,\mathrm{local}}$ = 0.224 Hz. The free vibration frequency is at 0.113 Hz resulting in a gust load factor which is almost 4% above that of the reference case but safely outside any critical wind velocities (The global eigen mode shape portrays typical cantilever bending shape and is not depicted here.). The calculations for the along wind gust factor, *G*, follows in Table I-2:

The parabolic hyperboloid geometrical change is located in the chimney base; for this study it is assumed that the frequency response method may be used but in future more detailed investigations should adapt the method for this geometry.

Table I-2. Calculated values for the along wind base overturning moment of the model of synthesised top technologies.

| **Parameter** | **Value** |
|---|---:|
| Height of building, h [m] | 1,500 |
| Horizontal width of structure, b [m] | 160+ |
| Roughness length, $z_0$ [m] | 0.02 |
| Longitudinal turbulence intensity, $I_u$, at height h | 0.0891 |
| Roughness factor, r | 0.1782 |
| Peak factor for upwind velocity fluctuation, $g_v$ | 3.7 |
| Effective turbulence length scale, $L_h$ [m] | 3,499.6 |
| Background factor, B | 0.278 |
| Second order effects of turbulence intensity, w | 0.087 |
| Background response | 1.38 |
| First along-wind global free vibration frequency [Hz] | 0.113 |
| Peak factor resonant part of response, $g_f$ | 3.467 |
| Hourly mean wind speed at height h, $V_{h,\mathrm{mean}}$ [m/s] | 65.03 |
| Size factor for spatial correlation, S | 0.047 |
| Effective reduced frequency, N | 6.081 |
| Spectrum of turbulence in wind stream, E | 0.135 |
| Structural damping capacity given as fraction of critical damping, $\varsigma$ | 0.0143 |
| **Gust factor, G** | **1.558** |
| Mean base overturning moment [N.m] | 2.69e+11 |
| **Design peak base overturning moment [N.m]** | **4.19e+11** |

Note that although the base of the chimney is 480 meter wide and not only 160 meter, the 160 meter value is used as a width parameter. The yielded gust factor must, from this perspective, be considered *upper limit*.

The across wind moment is not a threat to structural integrity, although close to the critical velocity – Figure I-2.

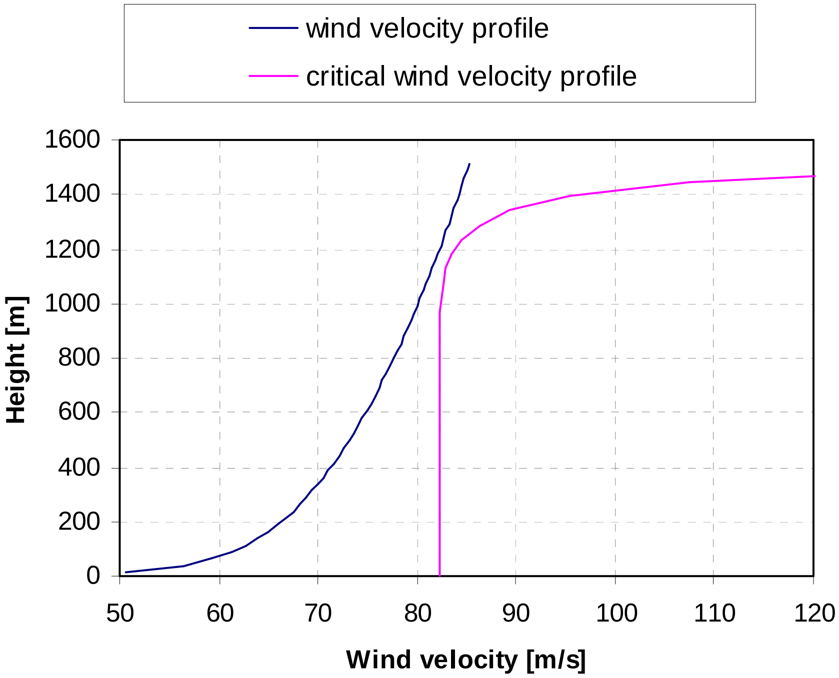


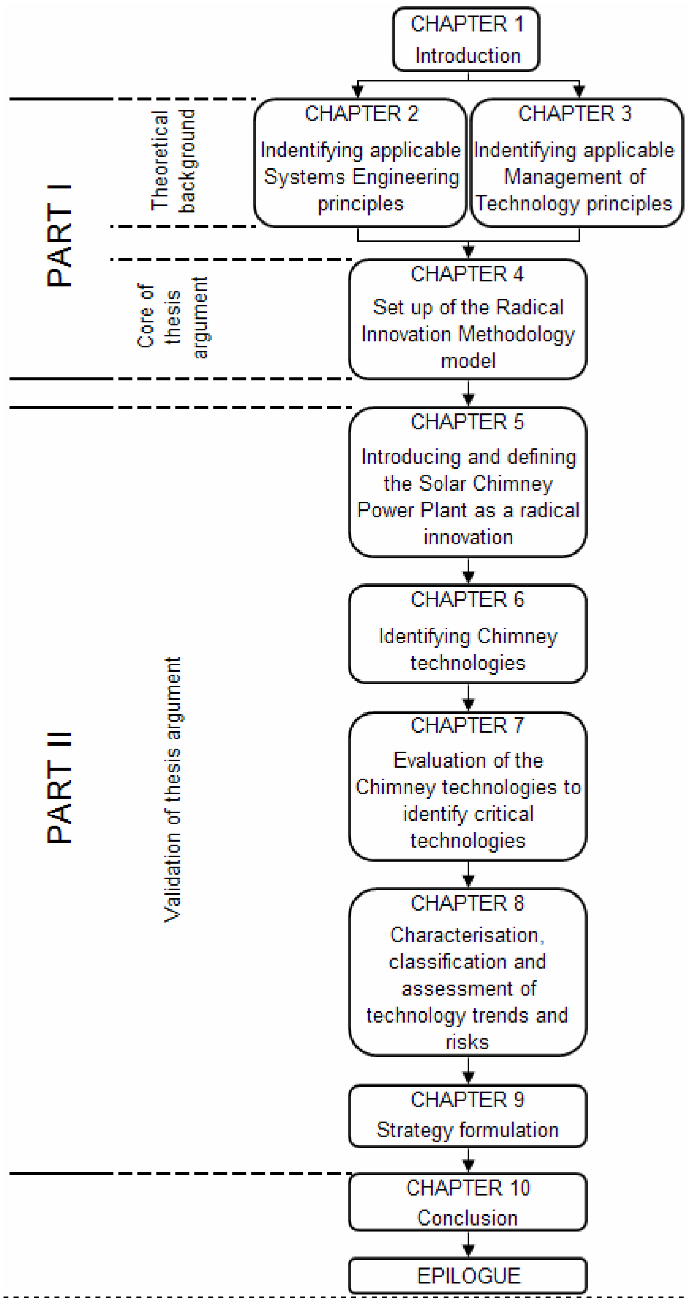
Figure I-2. Proximity of wind velocity profile to critical velocities – synthesised (epilogue) model.

# A methodology for radical innovation
## – illustrated by application to a radical Civil Engineering structure

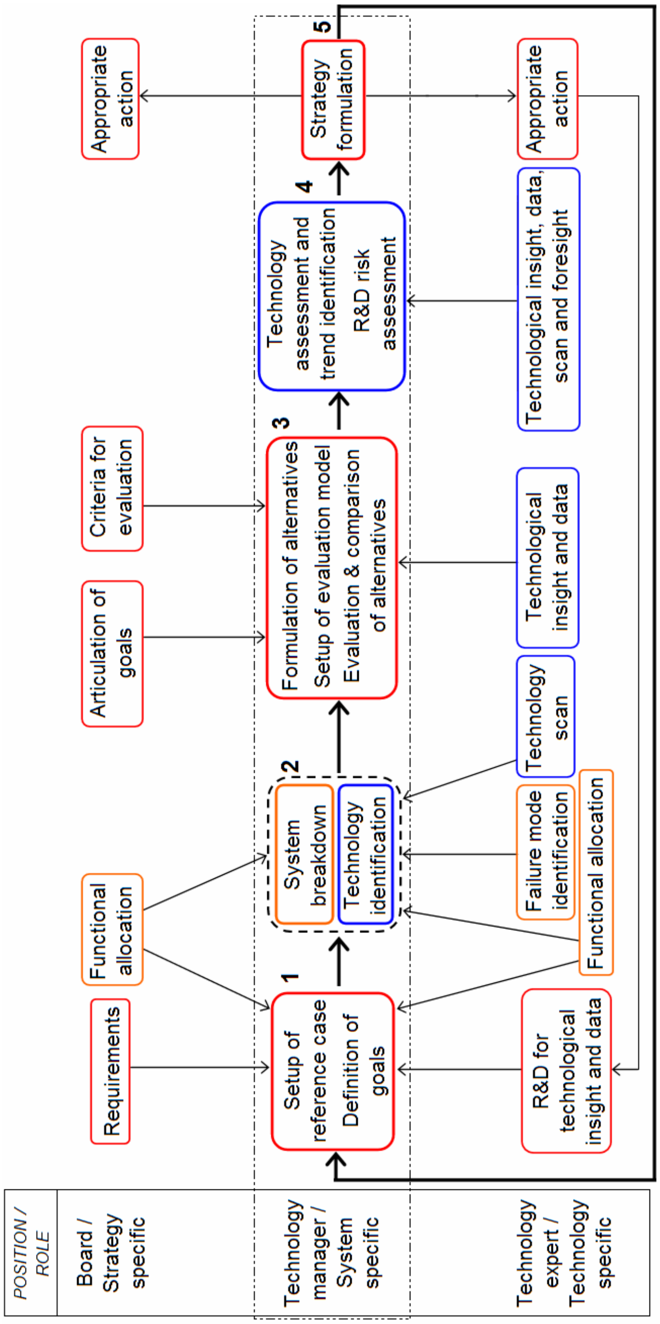
### THESIS STATEMENT

*Radical innovation can be systematised through the synthesis of existing theory to form a basis for strategic decision making.*

### DISSERTATION FLOW



## GRAPHICAL REPRESENTATION OF THE RADICAL INNOVATION METHODLGY



## RADICAL PERFORMANCE REQUIREMENTS FOR THE CHIMNEY

*GENERAL:*

*Clean, non oil-using, cost-effective* solutions are sought

*CHIMNEY SPECIFIC:*

Levelised electricity cost = R1.00/kWh
Critical buckling factor = 5.0
Frequency response load factor = 1.50