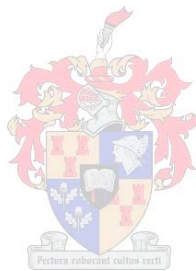# A Reconfigurable Manufacturing System for Thermoplastic Fibre-Reinforced Composite Parts: A Feasibility Assessment

by
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*Thesis presented in partial fulfilment of the requirements for the degree of
Master of Engineering (Mechatronic) in the Faculty
of Engineering at Stellenbosch University*

Supervisor: Prof. Anton H. Basson

March 2015

Declaration

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Date 12 February 2015

Abstract

A Reconfigurable Manufacturing System for Thermoplastic Fibre-Reinforced Composite Parts: A Feasibility Assessment

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The South African manufacturing industry plays a pivotal role in the growth of its local economy. Modern manufacturing requirements include the ability to respond quickly to product variability, fluctuations in product demand and new process technologies. The reconfigurable manufacturing paradigm has been proposed to meet the demands of the new manufacturing requirements. In order to assess the feasibility of incorporating automated, reconfigurable manufacturing technologies into the production process of thermoplastic fibre-reinforced composite parts, a system, based on the thermoforming process, that implements these technologies was developed and evaluated. The assessment uses a seat pan for commercial aircraft as case study.

Aspects that were addressed include the architecture, configuration and control of the system. The architecture and configuration addressed the sheet cutting, fixturing, reinforcing, heating, forming, quality assurance and transportation. The control, implemented using agents and based on the ADACOR holonic reference architecture, addresses the cell control requirements of the thermoforming process.

An evaluation of the system's reconfigurability and throughput is performed using KUKA Sim Pro. The evaluation of the system's throughput is compared to the predicted throughput of the conventional technique for manufacturing thermoplastic fibre reinforced composite parts in a thermoforming process.

The evaluation of the system's performance show that the system designed in this thesis for the manufacture of a thermoplastic fibre-reinforced composite seat pan sports a significant advantage in terms of throughput rate, which demonstrates its technical feasibility. The evaluation of the system's reconfigurability show that, through its ability to handle new hardware and product changes, it exhibits the reconfigurability characteristics of modularity, convertibility, integrability and scalability.

Uittreksel

'n Herkonfigureerbare Vervaardigingstelsel vir Termoplastiese Veselversterkte Saamgestelde Onderdele: 'n Uitvoerbaarhuidstudie

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Maart 2015

Die Suid-Afrikaanse vervaardigingsbedryf speel 'n sentrale rol in die groei van die plaaslike ekonomie. Moderne vervaardiging vereistes sluit in die vermoë om vinnig te reageer op die produk veranderlikheid, skommelinge in die produk aanvraag en nuwe proses tegnologieë. Die herkonfigureerbare vervaardiging paradigma is voorgestel om te voldoen aan die nuwe produksie vereistes. Ten einde die uitvoerbaarheid van die integrasie van outomatiese, herkonfigureerbare vervaardiging-tegnologieë in die produksieproses van veselversterkte saamgestelde onderdele te evalueer, is 'n stelsel, gebaseer op die termo-vormingsproses, wat sulke tegnologieë implementeer, ontwikkel. Die assessering gebruik 'n sitplek pan vir kommersiële vliegtuie as gevallestudie.

Aspekte wat aangespreek is sluit in die argitektuur, konfigurasie en beheer van die vervaardigingstelsel. Die argitektuur en konfigurasie spreek aan die sny, setmate, versterking, verwarming, vorm, gehalteversekering en vervoer van n veselversterkte saamgestelde sitplek pan in 'n termo-vormingsproses. Die beheer, geïmplementeer deur die gebruik van agente en gebaseer op die ADACOR holoniese verwysing argitektuur, spreek die selbeheervereistes van die termo-vormingsproses aan.

'n Evaluering van die stelsel se herkonfigureerbaarheid en deurvoer word gedoen met die behulp van KUKA Sim Pro. Die evaluering van die stelsel se deurvoer word vergelyk met die deurvoer van die konvensionele vervaardigingsproses vir termoplastiese vessel-versterkte saamgestelde onderdele in 'n termo-vormingsproses.

Die evaluering van die stelsel se prestasie toon dat die stelsel wat in hierdie tesis ontwerp is vir die vervaardiging van 'n termoplastiese vessel-versterkte saamgestelde sitplek pan, hou 'n beduidende voordeel, in terme van deurvloeikoers, in wat die stelsel se tegniese haalbaarheid toon. Die evaluering van die stelsel se herkonfigureerbaarheid wys dat, deur middel van sy vermoë om nuwe hardeware en produk veranderinge te hanteer, die stelsel herkonfigureerbare einskappe van modulariteit, inwisselbaarheid, integreerbaarheid en skaalbaarheid vertoon.

Acknowledgements

I would like to acknowledge, with appreciation, the contributions, comments, suggestions, constructive criticisms and financial assistance from the following contributors who all helped to make this thesis possible:

First and foremost I would like to thank **Professor Anton H. Basson** for his patience, motivation and enthusiasm. His vast knowledge and experience has also been a guiding light throughout my research. It was truly an honour to be part of his research group. I would also like to acknowledge fellow researchers **Karl Kruger**, **Anro Le Roux**, **Reynaldo Rodriguez** and **Clint Steed** for sharing their knowledge, opinions and technical expertise, particularly from the field of reconfigurable manufacturing systems.

I would also like to acknowledge several people from industry who have all contributed their practical experience and knowledge. Firstly, I express my gratitude to **Artho van der Westhuizen** from AAT Composites for his invaluable time and technical contributions from the field of composites. Secondly, I would like to give a special thanks to **Harm Albers** and **Gerjo Hultink** from TenCate. Their enthusiasm, friendliness and invaluable expertise from the field of composites made the long meetings with them on hot summer days truly worthwhile and enjoyable.

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Abbreviations

ACL	Agent Communication Language
ADACOR	Adaptive Holonic Control Architecture
ADE	Agent Development Environment
AFP	Automated Fibre Placement
AHP	Analytical Hierarchy Process
ATL	Automated Tape Layup
CFP	Call-for-Proposal
CNC	Computer Numerically Controlled
CNP	Contract Net Protocol
DLL	Dynamic Link Library
DMS	Dedicated Manufacturing System
FIPA	Foundation for Intelligent Physical Agents
FMS	Flexible Manufacturing System
FRC	Fibre-reinforced Composite
GUI	Graphical User Interface
HMI	Human-Machine Interface
HMS	Holonic Manufacturing System
HMC	Holonic Manufacturing Consortium
HSS	High Speed Steel
IMS	Intelligent Manufacturing System
MADRG	Mechatronics, Automation & Design Research Group
MAS	Multi-Agent System
MCU	Microcontroller Unit
OCX	Object linking and embedding Control Extension
OPC	Object linking and embedding for Process Control
PC	Personal Computer
PCD	Polycrystalline Diamond
PEI	Polyetherimide
PLC	Programmable Logic Controller
PP	Polypropylene
PPR	Proportional Pressure Regulator
PPS	Piezoresistive Pressure Sensor
PROSA	Product-Resource-Order-Staff-Architecture
QDC	Quick Die Change
RTL	Reinforced Thermoplastic Laminate
RMS	Reconfigurable Manufacturing System
UML	Unified Modelling Language
XML	Extensible Markup Language

1. Introduction

1.1 Background

The manufacturing industry plays a pivotal role in the growth of local and global economies. South Africa's manufacturing industry added 12.6 per cent to the Gross Domestic Product in the first quarter of 2013 (Statistics South Africa, 2013). This represents a drop of 1.2 percentage points since the first quarter of 2012. This decline is not isolated to South Africa, but is a global trend as shown by UNStats (2013) and Perry (2012). These statistics underline the importance of the manufacturing industry, but also indicates the inadequacy of present manufacturing systems. Joffe *et al.* (1995) showed that, in South Africa's case, this inadequacy stems from the declining productivity of these manufacturing systems. Setchi & Lagos (2004) suggest that this poor performance is due to the inherent inability of current manufacturing systems to adapt to dynamic market conditions which is demanding ever increasing responsiveness to product variability, fluctuations in demand and new process technologies.

To remedy this and improve manufacturing responsiveness, researchers in both academia and industry are investigating new manufacturing paradigms. One paradigm, reconfigurable manufacturing, has been proposed by Koren *et al.* (1999). Testament to its acceptance in academia and the potential for industry, this manufacturing paradigm has been recognised by several studies (Setchi & Lagos, 2004) as a priority area for research in manufacturing. One of these studies, the Delphi study (Committee on Visionary Manufacturing Challenges, 1998), conducted by the National Research Council in the USA gave reconfigurable manufacturing systems (RMS) the highest priority for research in manufacturing and has identified it as one of the six key manufacturing challenges for the year 2020.

The research proposed here forms part of a joint research effort into reconfigurable manufacturing systems by the Mechatronics, Automation and Design Research Group (MADRG) at the Department of Mechanical and Mechatronic Engineering at the University of Stellenbosch. The research builds on the previous research in the group, but is the first activity in a new project aimed at evaluating the use of reconfigurable manufacturing technologies for the manufacture of fibre-reinforced composite (FRC) parts.

AAT Composites, a company specializing in the production of performance composite parts for the aviation industry, is currently looking into using thermoplastic FRC materials for the manufacture of various seat parts for the commercial aviation industry. Important aspects related to the manufacturing process include product variations of the seat parts and auxiliary attachments, requirements for traceable and repeatable quality, increasing the throughput rate of composite parts and reducing labour costs. These aspects have strong synergies with the goals of the MADRG's research in RMSs. The production of seat parts by AAT Composites therefore serves as an excellent case-study and has steered this research to specifically focus on integrating automated reconfigurable manufacturing technologies into the production process of thermoplastic FRC parts.

1.2   Objective

The main objective of this research is to assess the feasibility of an automated reconfigurable manufacturing system for the production of thermoplastic fibre-reinforced composite parts, using a seat pan for commercial aircraft seats as a case study.

1.3   Motivation

The production process of FRC parts is a prime example which exhibits the poor responsiveness of current manufacturing systems, i.e. poor responsiveness to product variability and new process technologies. The manufacturing process is unresponsive to product variability, since it uses dedicated tooling (for example dedicated moulds and fixtures). The process suffers from slow production rates, since it is largely labour intensive and requires the controlled layup of highly flexible and fragile material to fabricate the complex geometries often required from FRC parts.

In order to stay competitive in the new dynamic market environment, which is characterised by fluctuations in product demand and increasing product variability, companies manufacturing FRCs are looking for automated systems that are able to provide flexibility in production quantities and which are able to handle a family of products. Reconfigurable manufacturing systems potentially offer this responsiveness, but no research into the feasibility of RMSs in this role has been found. Therefore, the research proposed here is aimed at assessing the suitability of RMSs in this regard, using as a case-study the production of a FRC seat pan.

1.4   Scope

The stages normally required for manufacturing thermoplastic fibre-reinforced composite parts are shown in figure 1. It can be seen that the first stage has several manufacturing aspects, which can be broadly classified into forming, layup, moulding and injection techniques.
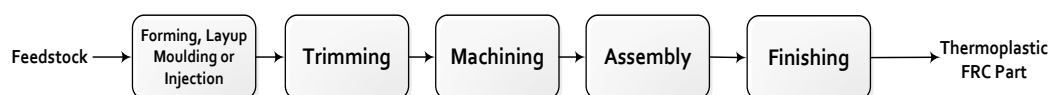
Figure 1: Stages of the manufacture of thermoplastic fibre-reinforced composite parts

For the sake of limiting the scope of the research in this thesis, only the first stage of the manufacturing process, as shown in figure 1, will be considered. Secondary processes such as machining, trimming, assembly and finishing will be considered in future research projects.

2. Literature Review

2.1 Introduction

This chapter starts with a discussion of manufacturing systems by firstly demonstrating the need for a new paradigm in manufacturing. This is done by outlining the current market conditions and demonstrating why traditional manufacturing systems are ill-suited for these market conditions. This is followed by a brief review of RMSs where RMSs are compared to conventional manufacturing systems, key system features required for reconfigurability are outlined and the technologies enabling reconfigurability are discussed. The chapter then continues with a discussion on the control of manufacturing systems by firstly reviewing the conventional approaches used and outlining their disadvantages. This is followed by presenting an alternative approach for the control of manufacturing systems which possibly holds many advantages. A review of the technologies suitable for implementing this alternative approach is then provided.

The chapter also reviews fibre-reinforced composites (FRCs) by firstly contrasting the two types of polymer composites used in the FRC industry, namely thermoset and thermoplastic composites, to motivate why the latter received preference in this thesis. Finally, for the purpose of selecting the most feasible material and process combination (performed in chapter 3) for the automated manufacture of a thermoplastic FRC seat pan, a review is given of the intermediate thermoplastic FRC material forms and the current state of the automated manufacture of thermoplastic FRCs using these specific materials.

2.2 Manufacturing Systems

2.2.1 Conventional Manufacturing Systems

The manufacturing sector is a key driver for economic growth. In order to maximise this economic growth, manufacturing systems should be compatible with current market conditions. As pointed out by Koren & Shpitalni (2011), aggressive economic competition on a global scale has shaped the current market to demand a manufacturing system that should be responsive to product variability, fluctuations in product demand and new process technologies. Setchi & Lagos (2004) further pointed out that other challenges facing this manufacturing system include non-obsolescence, reliability and simplicity. As described below, conventional manufacturing systems, which include Dedicated Manufacturing Systems (DMSs) and Flexible Manufacturing Systems (FMSs), are ill-suited for this new competitive market environment.

Dedicated Manufacturing Systems use dedicated production lines that focus on the production of a single product at a high rate and high volume over a long period. These lines are constrained to a single product since they are based on fixed automation. This production methodology clearly does not satisfy current market conditions, since DMS are not scalable as they have fixed cycle times and capacity (Koren & Shpitalni, 2011). They are also structurally inflexible and therefore cannot

cost-effectively adapt to fluctuations in product demand and satisfy demands in product variability. These dedicated lines therefore quickly become obsolete when product variants, new products or more products need to be produced.

Flexible Manufacturing Systems use computer-numerically-controlled (CNC) machines that are flexible systems that support product variety. However, two aspects make the FMS paradigm unsuitable for the current market. Firstly, the CNC machines are mostly equipped with propriety control systems which mean future modifications of the system are either very difficult or impossible and, secondly, these machines are characterized by single-tool operations making these systems unable to respond to fluctuations in product demand in an economically feasible manner (Koren & Shpitalni, 2011).

In the light of the above, it is clear that an alternative, more cost-effective and more responsive manufacturing system is required. This manufacturing system must be able to adjust its production capacity, respond to fluctuations in product demand and adapt its functionality to produce new products. In response to this need, Koren *et al.* (1999) proposed a new manufacturing approach titled Reconfigurable Manufacturing Systems.

2.2.2   Reconfigurable Manufacturing Systems

Koren & Shpitalni (2011) describe an RMS as a manufacturing system designed at the outset for rapid change in structure, as well as hardware and software components, in order to quickly adjust production capacity and functionality within a part family in response to sudden changes in market or regulatory requirements. This new paradigm is widely recognized in both academia and industry as a possible solution to the challenges the manufacturing industry currently faces (Committee on Visionary Manufacturing Challenges, 1998). Table 1 reviews the aforementioned arguments by comparing system features of RMSs to the traditional manufacturing systems, DMSs and FMSs.

Table 1: Comparison of RMSs to DMSs and FMSs (Dashchenko, 2006).

	DMS	FMS	RMS
System Structure	Fixed	Adjustable	Adjustable
Machine Structure	Fixed	Fixed	Adjustable
System Focus	Part	Machine	Part Family
Scalability	No	Yes	Yes
Flexibility	No	General	Customised
Simultaneous Operating Tool	Yes	No	Yes
Productivity	High	Low	High
Lifetime Cost	Low*	High	Medium

* only when at full capacity

2.2.2.1   Key Features of Reconfigurable Manufacturing Systems

In order for a manufacturing system to be reconfigurable, it must possess six core characteristic features (Koren & Shpitalni, 2011) which are detailed below. These characteristics apply to the manufacturing system on a system level, machine level and control level.

i.   **Modularity**: All functional components (both software and hardware) of the manufacturing system need to be modular. This allows the functional components to be replaced, rearranged or upgraded in order to adapt the functionality of the system.

ii.   **Integrability**: All functional components of the manufacturing system must be designed with standardised mechanical, informational and control interfaces. This allows the integration and future introduction of new technologies into the system.

iii.   **Customisation**: The capability and flexibility of the manufacturing system must be designed to produce any product variant within a product family in a given configuration.

iv.   **Convertibility**: The manufacturing system must be designed to quickly adapt the functionality of the system to product variants.

v.   **Scalability**: The manufacturing system must be designed to add or remove functional components in order to adapt the production capacity of the manufacturing system.

vi.   **Diagnosability**: Technologies and techniques (such as control technologies, statistics and signal processing techniques) must be integrated into the manufacturing system in order to monitor, diagnose and quickly resolve sources of quality and reliability.

According to Dashchenko (2006)**, t**hese characteristics are catalysts to achieve responsiveness, productivity and reduce life-cycle costs as shown in table 2. Customisation, scalability, convertibility and diagnosability aid adaptablity to production capacity and functionality, while modularity, integrability, diagnosability and convertibility reduce reconfiguration time and effort. Except for modularity, the other five characteristics help reduce the system lifetime costs.

Table 2: RMS Characteristics and System Goals (Dashchenko, 2006).

	Reconfiguration Time	Productivity	Life-Cycle Costs
Modularity	●		
Integrability	●		●
Customisation		●	●
Scalability		●	●
Convertibility	●	●	●
Diagnosibility	●	●	●

2.2.2.2   Technologies Enabling Reconfigurability

There are a number of technologies that needs to be developed and integrated into a manufacturing system for it to exhibit the reconfigurable characteristics described in the previous section. Since reconfiguration is required on three levels (Mehrabi et al., 2000), namely the machine-level, system-level and control-level, extensive research into technologies enabling reconfigurability at each of these levels has been conducted.

At the system-level, various machine configurations are normally required in order to manufacture a product family. Technologies which design, select and evaluate the optimal configurations in terms of cost, quality and reliability are needed. At the machine-level, modular machine tools are required. This means that machines must consist of separate components such that addition or modification of a component is possible. At the control-level, open-architecture controllers are required which exhibit various properties including autonomy, distributed, modularised and self-reconfigurable (Leitao, 2009).

2.3   Control of Manufacturing Systems

A manufacturing system comprises control components (e.g. PLCs, MCUs, etc.) and manufacturing entities (e.g. CNC machines, robots, conveyors, etc.). The responsibility of the manufacturing control system is to coordinate the manufacturing entities, using the control components, to transform raw materials into finished products. The control architecture defines the relationship between the control components, both with regard to their position and the way they interact. The ability of the control system to effectively coordinate the manufacturing entities is a strong function of the relationships between the control components, as defined by the control architecture. Therefore, the proper definition of a control architecture is an important prerequisite for an effective manufacturing control system.

2.3.1   Conventional Control Architectures

Three types of control architectures, namely centralized, hierarchical and heterarchical architectures, are conventionally used for manufacturing control systems. These three architectures are shown in figure 2, where the squares represent control components, circles represent manufacturing entities and interconnecting lines represent control relationships.

(a) Centralized Control Architecture   (b) Hierarchical Control Architecture   (c) Heterarchical Control Architecture
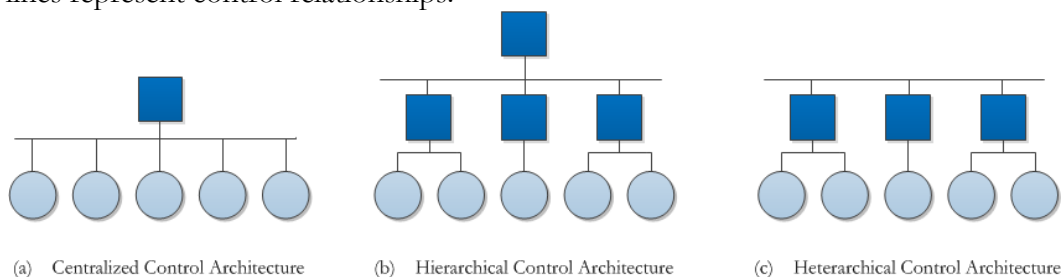
Figure 2: Conventional control architectures applied in manufacturing control systems.

In the centralized architecture a single, centralized control unit (such as an industrial PC) serves as the control component while the manufacturing entities, which possess a low level of intelligence, are dispersed throughout the manufacturing environment. All information processing and process planning are concentrated in the centralized control unit from which control commands are sent and executed by the manufacturing entities. The centralized control unit receives feedback information from the manufacturing entities which it uses to perform control decisions to achieve the global control objective.

Although the centralized nature of this architecture makes global optimization readily achievable and feedback information easily attainable, the inherent nature of the centralized approach may decrease the speed of response due to the (possibly) large processing overhead of the central control unit. This especially becomes true as the manufacturing system becomes larger.

The hierarchical architecture separates the central control unit found in the centralized architecture into several distinct control levels, such that the control architecture takes on a pyramidal structure. As a consequence, control functions are distributed with each control level responsible for information processing and process planning of a particular domain. At the top of the pyramid a control component is responsible for setting global goals and formulating long-term strategies (Dilts et al., 1991). This control architecture uses a master-slave philosophy in that the control activities of lower control levels are determined by their higher control levels.

The hierarchical nature of this architecture holds several advantages compared to the centralized control architecture. As a consequence of the distributed nature of this architecture, the control system can be easily modified by adding or removing control components according to manufacturing requirements. This aspect also reduces the computational overhead required by individual control components, possibly leading to a more responsive control system. Due to this modifiable nature, redundancy can be incorporated implying a high fault-tolerance. However, there are many short-comings of the hierarchical approach, including the high costs related to obtaining fault-tolerance and the increased system complexity potentially resulting in poorer system reliability (Duffie et al., 1988). Also, as indicated by Dilts *et al.* (1991), a whole sector of the manufacturing system may become paralyzed if inter-level communications between control components fail.

In order to circumvent the shortcomings of the previous architectures, a completely distributed architecture, called the heterarchical architecture, has been proposed (Duffie & Piper, 1987). This architecture breaks down the hierarchically structured, master-slave relationship between control components by locally distributing the control components and by providing full autonomy in their decision making. All information processing and process planning are shared among the control component while a cooperative approach is used to reach the control goal.

The autonomous nature of this architecture brings with it many advantages. As pointed out by Dilts *et al.* (1991), local autonomy implies a high fault-tolerance, while reduced coupling among the control components reduces the complexity leading to reduced development and maintenance times. However, a number of disadvantages are also associated with the autonomous nature of this architecture. Several are pointed out by Dilts *et al.* (1991), however Duffie & Piper (1987) point out the major drawback of this architecture in that the objective of optimizing overall system performance competes with the objective of maintaining full local autonomy.

2.3.2   Holonic Manufacturing Control Architectures

It was pointed out in the previous section that global production optimization is readily achievable in centralized and hierarchical control approaches, but their structure makes them inherently fault intolerant. On the other hand, the heterarchical control approach is highly fault tolerant due to its distributed and autonomous nature, but global production optimization is difficult to achieve since each control component has only a partial view of the system. In order to integrate the global optimization ability of the hierarchical approach with the fault-tolerance of the heterarchical approaches, the Intelligent Manufacturing Systems (IMS) consortium (Intelligent Manufacturing Systems, 1990) started conducting research in the early 1990's into new manufacturing control approaches. This research yielded the holonic control approach (Christensen, 1994) which is inspired by the philosophical concepts developed by Arthur Koestler (Koestler, 1969).

In Koestler's book, *The Ghost in the Machine*, (Koestler, 1969) he observed that in social organizations and living organisms every identifiable unit can be decomposed into several basic units while simultaneously forming part of a larger unit. Koestler therefore concluded that any system exists simultaneously as both a part and a whole which led him to coin the term "holon". The term is a combination of the Greek word "holos", which means whole, and the suffix "on", which means part. Koestler pointed out that the hybrid nature of holons allow them to be both autonomous and cooperative, with the former property ensuring the system can handle disturbances, while the latter property ensures that the system can work together to achieve a greater goal.

The IMS consortium translated the holonic concept into a manufacturing setting and defined the (manufacturing) holon as an autonomous and cooperative building block of a manufacturing system for transforming, transporting, storing and/or validating information and physical objects (Van Brussel et al., 1998). By this definition, a holon can represent any physical or logical entity within a manufacturing system, such as a machine, an order, an operator or even a whole manufacturing system. The consortium also defined a holarchy as a system of holons that cooperates to achieve the system goal by combining their individual skills and knowledge (Leitao, 2009). Finally, a holonic manufacturing system (HMS) is defined as a holarchy which integrates the entire range of manufacturing activities (from order booking through design, production, and marketing) to realize the agile manufacturing enterprise (Leitao, 2009).

Two holonic reference architectures, PROSA (Van Brussel et al., 1998) and ADACOR (Leitao & Restivo, 2006), have gained popularity in the research community to guide the designer of holonic control systems. These are briefly discussed in the following sections.

2.3.2.1   PROSA (Product-Resource-Order-Staff-Architecture)

Van Brussel *et al.* (1998) identified three core responsibilities of any manufacturing control system, namely resource, logistical, and product and process management. Correspondingly, they identified three necessary holons: resource holon, order holon,

and product holon. A resource holon consists of a physical manufacturing resource and of an information processing part that controls the resource. Resource holons provide production capacity and functionality to the product and order holons. Product holons hold the product and process information required for the manufacture of a product and therefore acts as an information server to the resource and order holons. Order holons represent tasks in a manufacturing system and is responsible for ensuring a product is manufactured correctly and according to schedule. Figure 3 shows the three necessary holons together with the manufacturing information they exchange.
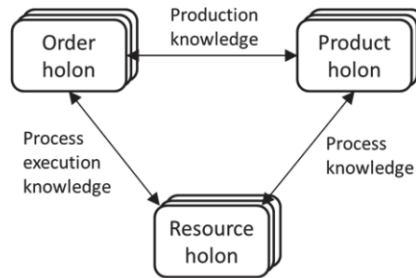
Figure 3: The three necessary holons proposed in the PROSA holonic reference architecture (Van Brussel et al., 1998).

A manufacturing system incorporating these three holons types will be able to operate in the face of disturbances due to the autonomous and self-reliant nature of holons. However, since these holons only have a partial view of the system, the manufacturing performance of the system cannot be guaranteed. Therefore, in order to introduce opportunities for optimisation, Van Brussel *et al.* (1998) added a hierarchical element in the form of a staff holon. In order to avoid rigidity in the system and maintain the autonomy of the basic holons, the staff holon only has an advisory role and cannot enforce any decision making onto the three basic holons.

2.3.2.2   ADACOR (ADaptive holonic COntrol aRchitecture)

Despite the novel PROSA architecture and other promising research into the development of holonic control systems, Leitao & Restivo (2003) identified the following aspects that still needed to be addressed:

i. In order to achieve global optimisation in distributed holonic systems, temporary hierarchies are required. The question is how should these hierarchies be formed, managed and removed.

ii. In order to be able to handle disturbances in distributed holonic systems, self-organisation and learning capabilities are required. The question is how to integrate these features into holonic manufacturing control systems.

In response to these questions, Leitao & Restivo developed the ADACOR holonic architecture (Leitao & Restivo, 2006). ADACOR, like PROSA, identifies three necessary holons: operational holons, task holons and product holons. The roles of these three holons are sufficiently similar to the resource, order and product holons identified in PROSA, respectively, to not warrant any further discussion.

In order to address the first aspect identified above, i.e. how should a decentralised control system evolve to achieve global optimisation, Leitao & Restivo introduced a fourth holon: the supervisor holon. The supervisor holon has a wider view of the system and has the ability to coordinate and form groups of holons (possibly with different subordination levels) in order to combine and aggregate their skills. The supervisor holon therefore has the ability to introduce hierarchy into a decentralised system which inherently adds opportunities for global optimisation. The generic structure of the ADACOR architecture is shown in figure 4.
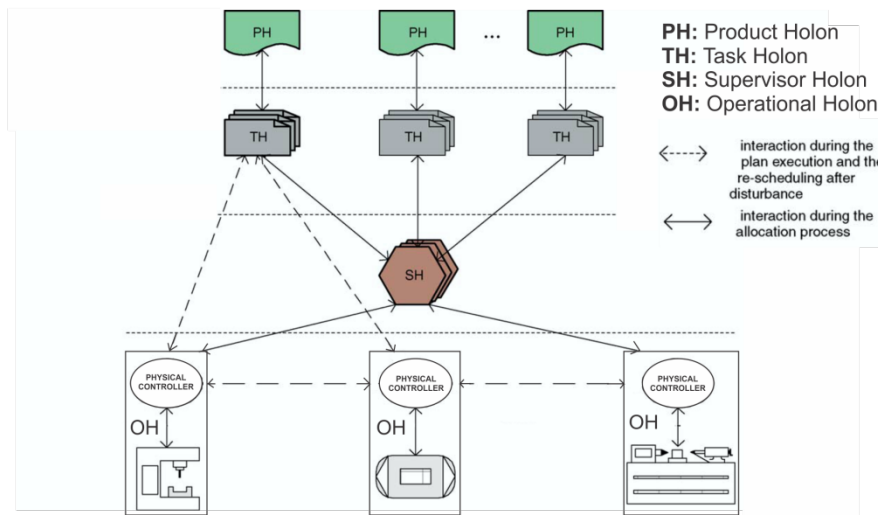
Figure 4: Generic ADACOR Architecture (Adapted from Leitao & Restivo, (2006)).

In order to address the second aspect identified above, i.e. how should self-organisation and learning capabilities be introduced in order to handle disturbances, Leitao & Restivo introduced the autonomy factor and a propogation mechanism. These features are discussed comprehensively in Leitao & Restivo (2006) and will not be discussed further.

Through the supervisor holon and the self-organisation and learning capabilities, the ADACOR architecture has the ability to combine the global optimasation abilities of hierarchical control structures and the high fault-tolerance of heterarchical control structures.

2.3.2.3   Holon Internal Architecture

Christensen (1994) proposed the first holon architecture and recommended that a holon consist of an information processing part and an optional physical processing part. As shown in figure 5, the physical processing part is subdivided into a manufacturing resource (such as a robot or conveyor) and the physical controller of the resource (such as a PLC). The information processing part is subdivided into a kernel, an inter-holon communications component and a physical interface component. The kernel regulates the behaviour of the holon. In a manufacturing control context, this includes the process planning, scheduling and plan execution (Leitao & Restivo, 2006). The inter-holon communications component is responsible

for communication between other holons using a standardised communications language and ontology (discussed in section 2.3.4.2). Finaly, the physical interface component handles the communication between the physical controller and the manufacturing resource.
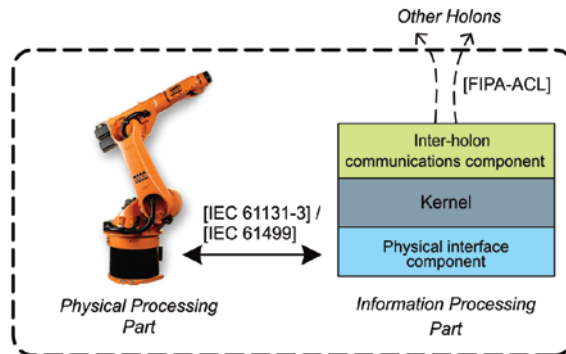
Figure 5: The proposed architecture of a holon (Adapted from Leitao (2009)).

The implementation of the information processing part of a holon has received considerable attention from the recearch community. As a result, two promising technologies are evaluated below: Agents and IEC 61499 function blocks.

2.3.3   IEC-61499 Function Block Control

The IEC-61499 function block architecture was developed by the Holonic Manufacturing Consortium (HMC) with the aim to meet the requirements of holons and their real-time control strategies (Christensen, 1994). It is partly based on the IEC-1131-3 standard, which is the well-known standard for languages used in PLCs for real-time control.

Important features of the IEC-61499 architecture are that the data flow and event flow between function blocks are separated, function blocks can move between devices making the manufacturing system more fault-tolerant, and function blocks can be added or removed within an application introducing the advantage of flexibility and scalability. However, the IEC-61499 architecture does not address negotiation, cooperation and deliberative decision making (Marik & Lazansky, 2007). As a result, most researchers (Fletcher & Deen, 2001; Christensen, 1994; Hall et al., 2005) propose the use of either the IEC-61499 or IEC-61131-3 standard for low-level, real-time control as shown figure 5.

2.3.4   Agent-Based Control

Software agents offer an attractive alternative approach for the implementation of distributed control systems compared to approaches such as the object-oriented programming and the function block standards. The latter approaches usually model distributed systems as software units that exchange data and commands, while agent technology models distributed systems as autonomous and self-reliant decision makers, called agents, which are able to communicate preferences, negotiate sub-goals and coordinate its intentions in order to achieve individual or system goals (Bussman et al., 2004).

In this section, a definition of agents and their properties are first given, after which a brief discussion of the communication and coordination infrastructure, which assist agents to achieve their goals, are discussed. A short review of the standards that guide the development of agents and the agent development platforms currently available is also given.

2.3.4.1   The Software Agent Concept

Although the agent term is widely used and significant research into agents has been conducted, there does not seem to exist a universally accepted definition of an agent. However, the definition by Leitao & Restivo (2003) is adopted here since it is more applicable to the manufacturing control context and has found currency with many researchers: "An autonomous component, which represents a physical or logical object in a system, capable to act in order to achieve its goals, and being able to interact with other agents, when it doesn't possess knowledge and skills to reach alone its objectives" (Leitao & Restivo, 2003).

With reference to a manufacturing control context, the most important features of agents are (Wooldridge & Jennings, 1995):

i.   **Autonomy** – agents have the ability to operate without the direct intervention of humans or other agents.
ii. **Sociality** – agents have the ability to interact with other agents using an agent communication language.
iii. **Reactivity** – agents have the ability to perceive data within their environment and can act to changes that occur within the environment.
iv. **Pro-activeness** – agents have the ability to take the initiative in order to fulfil its own plan or goal.

Other features not relevant to most manufacturing control applications, but can be included if necessary, are: An agent can be mobile, representing the ability to move between different nodes in a network. An agent can be truthful which ensures that it will not deliberately provide false information. An agent can be benevolent which means an agent will always be willing to help other agents in as far as it is not contrary to its own goals. An agent can be rational in that it will never prevent its own goals from being achieved. Finally, an agent can adapt its own capabilities and behaviour by learning from its environment.

A multi-agent system (MAS) is a system where two or more agents are resident, cooperating and/or competing to achieve individual or collective goals, and the achievement of these goals is beyond the capabilities and knowledge of the individual agents (Botti & Giret, 2008).

Bussmann (1998) and Christensen (2003) showed that agents offer the necessary tools to develop the information processing architecture of a holon. Botti & Giret (2008) performed an extensive comparison of the properties of agents and holons. They found that agents and holons are very similar and concluded that a holon is a special case of an agent. They are, therefore, in agreement with many researchers (Brennan & Norrie, 2001; Bussmann, 1998; Kruger & Basson, 2013) that the use of

agent technology is more suitable, compared to the IEC-61499 function blocks, for the implementation of the information processing part of a holon including the inter-holon communication as shown in figure 5.

2.3.4.2   Agent Coordination and Communication

In the context of agents, coordination is the process in which agents within a MAS engage to ensure that the community of agents act in a coherent manner (Nwana et al., 1996). As Nwana *et al.* explains, coherence here means 'how well a MAS behaves as a unit'. Bellifemine *et al.* (2007) list the following reasons why coordination may be required in MASs:

   i.   To prevent conflicts between agents.
   ii.   Goals of different agents may be interdependent.
   iii. Agents may have different capabilities and knowledge.
   iv.   A goal may be reached faster if multiple agents work on it.

Nwana *et al.* (1996) list several approaches including organisational structuring, multi-agent planning, negotiation and contracting which can be used for agent coordination. However, the last of these, formally termed the Contract-Net Protocol (CNP) (Smith, 1980), seems to have become one of the most popular methods (Vokrinek et al., 2007) used for agent coordination and will therefore be briefly reviewed next.

The premise of the CNP comes from the negotiation concept used by businesses in a market environment. In a bid to reach a goal, a business usually announces to external contractors a service it wants performed (since it does not have the knowledge or expertise to perform that service itself). Suitable contractors then tender their services to the business after which the business evaluates their tenders. Finally, the business awards the contractor with the best bid to perform the required service.

The CNP for MASs implements this flow of negotiation in a similar fashion as shown in figure 6. One agent, the initiator, requests a proposal from other relevant agents by issuing a call-for-proposal (CFP). The CFP specifies the service the initiator agent requires and may include additional conditions (for example, a deadline) related to the service. The other agents, the participants, receiving the CFP may then reply by either submitting or refusing the CFP. As soon as the initiator agent has received all replies, it evaluates the proposals and selects the best proposal(s). The initiator agent then notifies the agent(s) of the selected proposal(s) that their proposal has been accepted while also notifying the other participating agents that their proposals have been rejected. Finally, as soon as a participating agent, whose proposal was accepted, has completed the desired service, it informs the initiator agent that it is done. In the case that the participating agent failed to execute the service, it can notify the initiator agent accordingly.
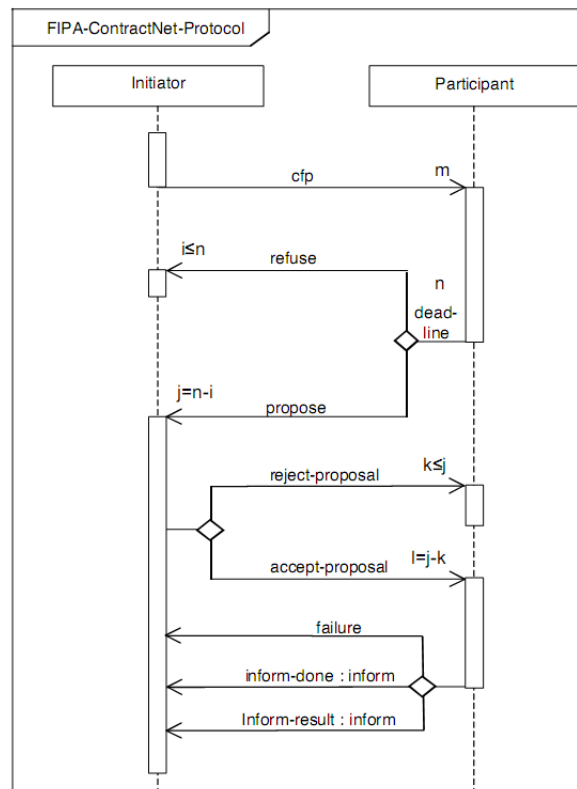
Figure 6: The Contract Net Protocol (The Foundation for Intelligent Physical Agents, 2002).

It is clear from the above that for coordination to occur, a communication protocol to exchange information and knowledge between agents is required. Currently, the protocol with possibly the largest uptake is the FIPA Agent Communication Language (FIPA-ACL) (The Foundation for Intelligent Physical Agents, 2002). For effective communication, each ACL message normally includes the following fields: a performative, the sender, the intended receivers, the content language, the ontology and the actual content of the message.

An example of a message using this language is as follows:

```
(request
    :sender AGENT1
    :receiver AGENT2
    :language FIPA-SL
    :ontology DOMAINVOCABULARY
    :content (STATUSOF (AGENT2))
    …
)
```

A performative (also known as a communicative act) is an indication of what action the sender agent wants to achieve by the act of communicating. In the above message, the performative is 'request' which means the sender agent requests the receiver agent to perform some action. The range of performatives have been standardised into different types of actions including interrogatives, which query for

information, excercitives, which asks for another action to be executed, referentials which share knowledge about the environment, phatics which establish, prolong or stop communication, paralinguistics which relate one message to another, and expressives which express attitudes, intentions or beliefs (Bellifemine et al., 2007). The content language is the syntax used to express the content of a message and therefore agents encode or parse content expressions according to this syntax. Finally, the ontology is a domain-specific vocabulary of symbols which is shared by all agents. This vocabulary ensures that all agents ascribe the same meaning to the symbols in a content expression.

2.3.4.3   Agent Standards and Development Platforms

There are a number of organisations and initiatives dedicated to the development of standards relating to software agent technology, such as the KSE (Patil et al., 1998), OMG (Milojicic et al., 1998) and FIPA (The Foundation for Intelligent Physical Agents, 1999). However, the FIPA standards have become the most widely used for the development of agent technologies. The FIPA standards address several aspects relating to the development of software agents. These aspects include agent architecture, inter-agent communication and agent management (Bellifemine et al., 2007).

When adopting an agent-based approach for developing a distributed control system, it is convenient to develop the agents using agent-oriented middleware which already provides the infrastructure for the development of agents. There are several platforms available for the development of agents. According to Bădică *et al.* (2011) and Vrba (2003), the platforms that are the most influential, active and well supported include ZEUS (Collins et al., 1998), FIPA-OS (FIPA-OS, 1999) and JADE (Bellifemine & Caire, 2000).

2.4   Fibre-Reinforced Composites, Material Forms & Manufacturing Processes

Polymer-based composites are divided into either thermoset or thermoplastic fibre-reinforced composites (FRCs). Thermoset FRC materials have been widely used in the composites industry for many years, however, thermoplastic FRC materials has recently received significant interest from both industry and the research community (IAPD, 2010). In order to motivate this trend, Appendix A briefly compares thermoset and thermoplastic FRCs.

Thermoplastic composite parts can be manufactured from using either intermediate material forms, normally called pre-pregs, where the reinforcing fibres have been pre-impregnated into the polymer matrix in a previous process, or from the constituting materials where the reinforcing fibres and polymer matrix components are combined in-process.

There are a large variety of intermediate thermoplastic material forms commercially available for the manufacture of thermoplastic FRC parts. These intermediate material forms are classified based on their fibre length, fibre architecture and matrix distribution. The fibre length can either be short, long or continuous; the fibre

architecture can either be uni-axial, bi-axial or multi-axial while the matrix distribution can either be partially consolidated, fully consolidated, commingled or powder impregnated. Various combinations of these attributes result in a wide range of intermediate forms that may be produced, however, the market demand for specific properties dictates the material forms that are being used commercially.

From a literature survey of the thermoplastic intermediate material forms used in industry, the most common forms that are used to manufacture thermoplastic fibre-reinforced composite parts are unidirectional pre-preg tapes, semi-preg fabrics, reinforced thermoplastic laminate sheets and moulding compounds (figure 7). Although these intermediate forms are inevitably more expensive on a cost/kg basis as compared to the dry material forms (also shown in figure 7), they may offer design advantages, manufacturing convenience and reduced downstream processing costs. Based on these arguments, only the intermediate material forms will be considered from here on. To facilitate a better understanding of these material forms and for the purpose of selecting the most feasible material form and automated manufacturing process for the seat pan (described in chapter 3), a brief description of the intermediate material forms and their associated automated manufacturing processes are given Appendix B.
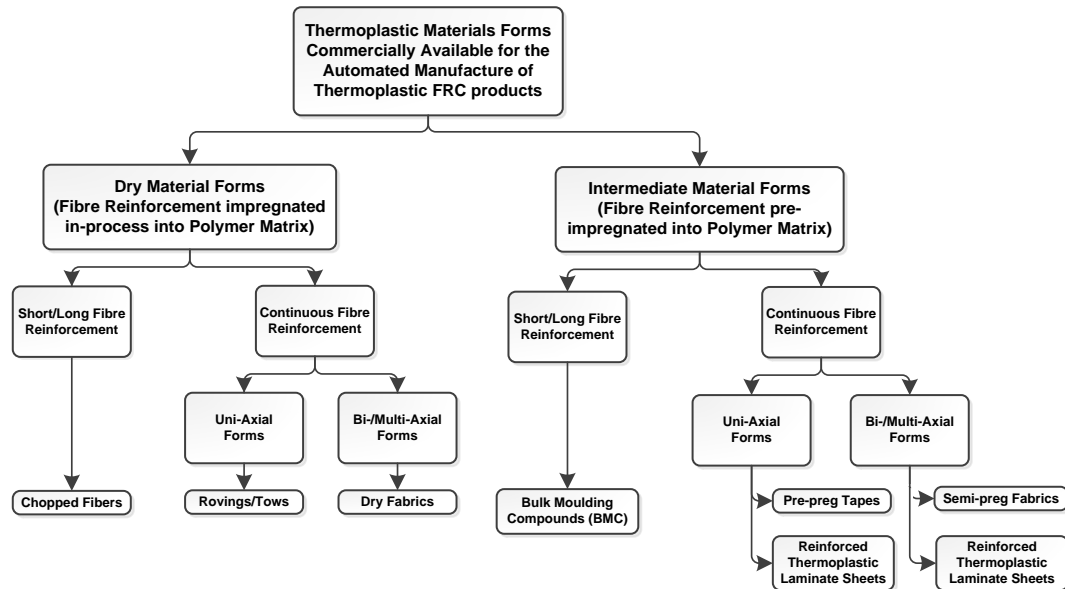
Figure 7: Materials suitable for the automated manufacture of thermoplastic fibre-reinforced composite products.

3.   Manufacturing Process Selection

3.1   Introduction

AAT Composites, located in Cape Town, South Africa, is a company that specializes in the design and manufacture of aircraft interior structures using carbon or glass FRC materials. Their focus is mainly related to seating components, which include backrests, armrests and side arms, among others (figure 8).

Figure 8: Typical economy class seat used in commercial aircraft (Adapted from Dowty & Yurchenco (2006)).

The company has extensive experience in thermoset prepreg materials using autoclave, press-clave, frame and vacuum bag moulding processes to manufacture these seat components. The press-clave moulding process, which is their fastest process among the aforementioned processes, has a maximum proven capacity of 3000 mouldings per week. Although seemingly fast, this represents only 25 mouldings per hour. This slow throughput rate, which is limited by the long curing times required by thermoset resins, coupled with low-cost manual labour, gave the company little incentive to automate its production processes.

In 2013 the company decided to expand their product portfolio by including a seat pan (figure 9) to the range of seating components offered by the company. The main purpose of the seat pan is to serve as a platform upon which a seat cushion can be located and under which a support structure can be coupled.

As a result of the higher throughput rate required, product variations of the seat pan, requirements for traceable and repeatable quality and a desire to reduce labour costs, the company collaborated with the Mechatronics, Automation and Design Research Group to investigate alternative materials and automated processes. The parties agreed that an automated reconfigurable production cell using thermoplastic FRC materials may have the potential to meet these requirements.

Note: Dimensions represent approximate overall seat-pan dimensions.
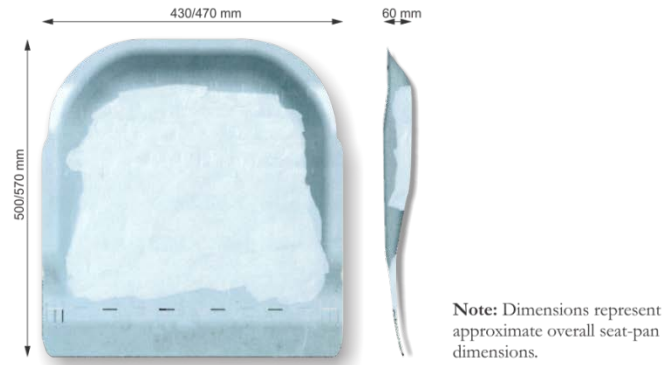
Figure 9: Seat-pan by AAT Composites. Due to intellectual property restrictions, technical details in the image have been painted out.

It is evident from the literature review given in Appendix B that there are numerous manufacturing processes available for the automated manufacture of small, geometrically complex thermoplastic FRC parts. This chapter serves to select from these the most promising process to manufacture a seat pan, similar to that used in a wide range of economy class seats in Airbus commercial aircraft. The selection of the most promising manufacturing process will be performed in the following sections using the analytical hierarchy process (AHP) developed by Saaty (1987).

3.2 Selection of Manufacturing Process using the Analytical Hierarchy Process

The AHP is a multi-criteria decision making approach and is a theoretically sound and widely accepted methodology (Bhushan & Rai, 2004). It has garnered wide-spread use across multiple domains including the business (Machado et al., 2003), manufacturing (Angelis & Lee, 1996), banking (Arbel & Orgier, 1990) and defence (Forman & Gass, 2001) industries among others (Vaidya & Kumar, 2006). It allows the use of both empirical data and subjective judgements of the decision maker(s) in the decision making process. The methodology is a five step process as shown in figure 10 and will be followed in this section to determine the most feasible automated manufacturing process for the manufacture of the seat pan. There are several decision-making software packages which implement the AHP with Expert Choice (Expert Choice, 2014) being one of the most widely used. Therefore, this software package will be used to implement the AHP.

3.2.1 Goal, Criteria and Alternatives

The first step in the AHP is to decompose the decision-problem into a hierarchy consisting of a goal, main criteria, sub-criteria and alternatives. The goal is the objective that is to be achieved, the main criteria and sub-criteria are the factors that affect the selection of the alternatives while the alternatives are the possible solutions to the goal. Decomposing the decision problem into a hierarchy helps to structure the relationships between the elements of one level with respect to the elements of a higher level.

AHP Process
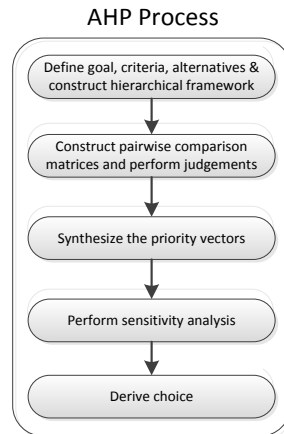
Figure 10: The five steps in the Analytical Hierarchy Process (AHP).

The goal in this project is to: "Select the most feasible automated manufacturing process for the manufacture of a seat pan". The main criteria are grouped into (i) Manufacturing performance requirements, (ii) Manufacturing constraints and (iii) Part geometry requirements. The sub-criteria include (i) rate, (ii) curvature complexity, (iii) local-reinforcements, (iv) size, (v) equipment cost, (vi) material cost and (vii) expertise. These are briefly discussed in sub-sections 3.2.1.1 to 3.2.1.3 to motivate why they are specifically considered. The alternatives are the manufacturing processes discussed in Appendix B which were deemed most suitable candidates for the automated manufacture of the seat pan. These include (i) ATL (or AFP) machines using pre-preg tape, (ii) Robotic Layup using pre-preg tape, (iii) Robotic Layup using semi-preg fabric and finally (iv) Thermoforming using reinforced thermoplastic laminates. The hierarchy showing the goal, criteria, sub-criteria and alternatives are shown in figure 11. It should be noted that other criteria such as mechanical performance, safety and quality requirements were not included since it is expected that all the materials in the manufacturing processes considered will be able to meet the performance, safety and quality requirements of the seat pan and therefore these criteria do not affect the selection process. In the following sub-sections, the main criteria, sub-criteria and alternatives will be generally referred to as variables for the purpose of explaining the application of the remaining steps in the AHP.
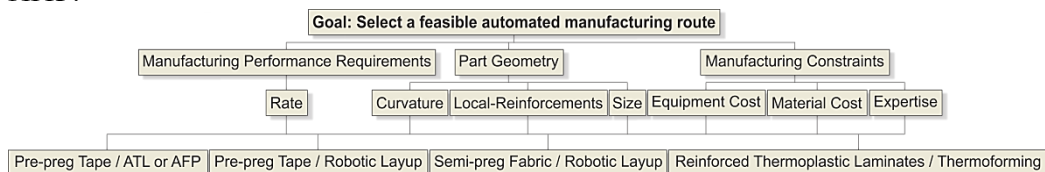
Figure 11: AHP hierarchy showing the goal, main criteria, sub-criteria, and alternatives.

3.2.1.1   Manufacturing Performance Requirements

i.   Throughput

The throughput rate is one of the most important factors determining the feasibility of a manufacturing process. The throughput rate must be matched against the minimum customer demand, but must also be fast enough to reach an economic break-even point as quickly as possible to justify the capital expenditure of the required machinery.

3.2.1.2   Part Geometry Requirements

An important step in selecting a feasible manufacturing process is to match the process capabilities of a manufacturing process to the geometric requirements of a product, since the shape-generating capabilities of different composite manufacturing processes are unique. The geometric requirements considered here include curvature complexity, part thickness and part size.

i.   Curvature Complexity

The complexity of features of a composite part is generally classified as single or double curvature complexity. Single curvature features are curved on one linear axis, while double curvature features are curved relative to two linear axes. Examples of single and double curved parts are shown in figure 12. Not all composite manufacturing processes are able to achieve similar complexity and therefore it is important to match the shape-generating capabilities of a process to the complexity requirements of a part.

Single Curvature Part   Double Curvature Part

Figure 12: Single and double curved parts (Adapted from Xinology (2014) and Birch (2009)).

The range of manufacturing processes considered in Appendix B are all able to manufacture doubly curved parts to some degree, however, some are able to achieve higher complexity than others. For example, the literature reviewed on these processes have shown that unidirectional tapes with robotic layup and thermoforming with reinforced thermoplastic laminates are able to yield more complex features compared to either ATL/AFP machines with unidirectional tapes or robotic layup with semi-preg fabrics.

ii. Local-reinforcements

Local-reinforcements are usually strategically placed on parts to increase their load bearing capacity or as a result of local stress concentrations (due to, for example, fasteners). A variant of the seat-pan considered in this project (which will be used for aircraft seats located near emergency exit locations) requires the application of reinforcements since regulatory requirements mandate that the load bearing capacity of such seat-pans need to be higher. It is therefore important to consider whether a manufacturing process allows the application of reinforcements. In the manufacturing processes reviewed in Appendix B, all the processes allow the application of reinforcements in situ except for the use of reinforced thermoplastic laminates in a thermoforming process. However, as reviewed in Appendix B, it is possible to use a secondary process prior to or after the forming process.

iii. Size

The maximum (or minimum) achievable size of a manufacturing process is inherently limited by the material and machinery employed. It is therefore important to select a manufacturing process which can produce a product to the required dimensions.

3.2.1.3   Manufacturing Constraints

The final step in selecting a feasible manufacturing process is to ensure that possible constraints, such as economic and skill constraints, are not violated. Therefore, the constraints considered here include equipment and material costs and the level of skill required in adopting a manufacturing process.

i. Equipment and Material Cost

Fixed and variable costs need to be kept as low as possible in order to reach a economic break-even point as fast as possible in any manufacturing process. Therefore, it is important to ensure that the equipment and material costs are viable.

ii. Required Expertise

The skill required in operating and maintaining equipment is an important factor for the selection of a manufacturing process. Manufacturing processes that demand high skill may lead to higher costs associated with personnel required to operate or maintain the equipment. It may also lead to downtime if specialists need to be sourced to repair equipment in the event of a breakdown. A manufacturing process with a lower required skill level is therefore normally preferred.

3.2.2   Pair-wise Judgement of Variables

The second step in the AHP is judgement of the variables (i.e. criteria, sub-criteria and alternatives) through a pair-wise comparison process. In this process the importance of two variables on one level are evaluated with respect to the variable higher in the hierarchy. This evaluation can be based on quantitative measures or experience (if the criteria are not measureable). Therefore, for a four level hierarchy

there are three types of judgements that should be made: (i) Judgements of the main criteria with respect to the goal, (ii) Judgements of the sub-criteria with respect to the main criteria and (iii) Judgements of the alternatives with respect to the sub-criteria. At the conceptual design stage precise quantitative measures are mostly not available to judge the relative importance of variables and for that purpose a nine-point scale, shown in table 3, was introduced by Saaty (1987). Experiments by Saaty and the experience of the many users of the AHP have proven the suitability of this scale to map the judgments of an individual to discrete numerical values which represent the relative importance of a variable (Harker & Vargas, 1987).

The pairwise comparison process is most easily implemented in a $n \times n$ matrix where n is the number of variables being compared. Each entry a_{ij} represents the importance of the ith variable relative to the jth variable. The main diagonal entries of the comparison matrices will always be 1 (i.e. $a_{ij} = 1 \; for \; i = j$) since identical variables cannot differentiate in importance. The off-diagonal entries must be such that $a_{ij} = \frac{1}{a_{ji}} \; for \; i \neq j$. This means that if the ith variable is judged, for example, to have an importance value of x compared to the jth variable (i.e. $a_{ij} = x$), then the jth variable must automatically be assigned an importance value of $1/x$ compared to the ith variable (i.e. $a_{ji} = 1/x$).

Table 3: Evaluation scale used to estimate the relative importance of variables in a pairwise comparison (Bhushan & Rai, 2004).

Option	Numerical value(s)
Equal	1
Marginally strong	3
Strong	5
Very strong	7
Extremely strong	9
Intermediate values to reflect fuzzy inputs	2, 4, 6, 8
Reflecting dominance of second alternative compared with the first	Reciprocals

As an example, the pairwise comparisons of the main criteria with respect to the goal are shown in table 4. It can be seen that, relative to the goal, the importance of the Manufacturing Performance Requirements (MPR) was assigned a value of 7 compared to the Part Geometry Requirements (PGR) which indicates that the former criterion was judged to have a 'very strong' importance (Table 3) compared to the latter criterion.

Table 4: Pairwise comparisons of the criteria with respect to the goal.

Goal	MPR	PGR	MC
MPR	1	7	3
PGR	1/7	1	1/5
MC	1/3	5	1

22

The pairwise comparisons for all levels of the hierarchy were implemented in Expert Choice. The pairwise comparison matrices are shown in Appendix C. The data in table 5, which was generated from the literature reviewed in Appendix B.3 on these manufacturing routes, was used as a reference for the judgements performed in these matrices.

Table 5: Data used as a basis for the pairwise comparisons.

Sub-Criteria	Alternatives			
	Pre-preg Tape / ATL or AFP	Pre-preg Tape /Robotic Layup	Semi-preg Fabric /Robotic Layup	Reinf. Therm. Lam. / Thermoforming
Rate[1]	800-1000 mm/s (10.5 min/part)	300 - 500 mm/s (12 min/part)	300 - 500 mm/s (12 min/part)	N/A (< 5 min/part)
Curv. Complexity	Simple	Simple-Complex	Simple	Simple-Very Complex
Reinforcement	Yes	Yes	Yes	No
Size	Small-Very Large	Small-Large	Small-Large	Small-Medium
Material Cost	Medium	Medium	Medium	High
Equipment Cost	Very High	Medium	Medium	High
Expertise	Very High	High	High	Medium

(1) The first value represents typical values found in literature. The second value is the time required to lay down a flat part of dimensions 500 mm × 500 mm × 3 mm using a material thickness of 0.25 mm thick and 35 mm wide with a 3 sec. delay/course. (In the case of fabric, the compaction roller is 35 mm wide).

3.2.3 Synthesis of most Feasible Manufacturing Process

The next step in the AHP is to synthesize the *overall* importance of the variables investigated. This is achieved by calculating priority vectors from the pairwise comparison matrices constructed in the previous step. The components of the priority vectors rank the importance of the variables relative to one another. The priority vectors are estimated by calculating the right principle eigenvector corresponding to the maximum eigenvalue of the pairwise comparison matrices. The method of determining the priority vectors is comprehensively covered by Cabala (2010) and is automatically calculated from the pairwise comparison matrices in Expert Choice.

As an example, the priority vector for the pairwise comparison matrix in table 4 is calculated as $w = [0.649 \quad 0.072 \quad 0.279]$. This ranks the importance of the main criteria and shows that the manufacturing performance requirements are considered the most important criteria affecting the decision of the manufacturing process. This is followed by the manufacturing constraints, while the part geometry requirements are considered the least important.

Expert Choice was used to derive all the priority vectors corresponding to the pairwise comparison matrices generated earlier and are given in Appendix C. Figure 13 summarises the priority vectors for all variables in a tree structure and figure 14 shows the ranking of the alternatives (manufacturing processes) calculated from these priority vectors. It is observed that the use of reinforced thermoplastic laminates in a thermoforming process is deemed the most feasible choice for the manufacture of the seat pan.
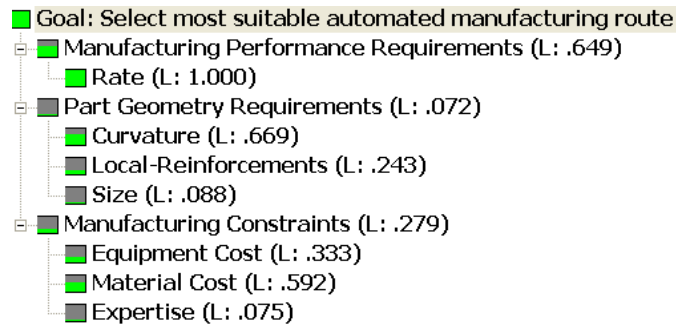
Figure 13: Tree structure of the goal, main criteria and sub-criteria. The values in the round brackets are the priority values with respect to the leaf higher in the tree.
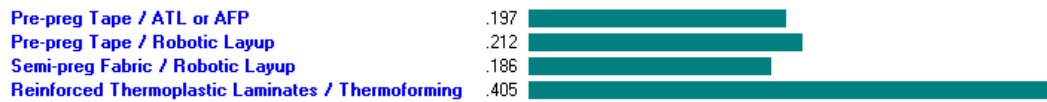
Figure 14: Overall priority vectors ranking the manufacturing processes.

3.2.4   Sensitivity Analysis

The final step in the AHP is to perform a sensitivity analysis. In this step, the components in the priority vectors of the criteria are varied. By varying the priority vectors of the criteria, the components in the priority vector of the alternatives change and therefore the rank of the alternatives may change. Therefore, the aim of the sensitivity analysis is to determine whether the rank of the alternatives is robust against changes in the priority vectors of the criteria – particularly the rank of the first alternative since this is usually of most interest.

The sensitivity analysis has been performed in Expert Choice. The components in the priority vector of the main criteria have been varied by $\pm$20% to observe what effect it has on the rank of the manufacturing processes[1]. The results are given in table 6 and graphically shown in figure 15.

Table 6: Sensitivity analysis to observe how robust the rank of the alternatives is to changes in the priority vectors of the main criteria.

Rank	Initial Ranking	MPR		MC		PGR	
		20%	-20%	20%	-20%	20%	-7.2%
1	RTL/Ther (0.405)	RTL/Ther (0.520)	RTL/The r (0.289)	RTL/Ther (0.328)	RTL/Ther (0.481)	RTL/Ther (0.397)	RTL/Ther (0.407)
2	PPT/RL (0.212)	PPT/ATL (0.183)	PPT/RL (0.230)	PPT/RL (0.249)	PPT/ATL (0.188)	PPT/RL (0.221)	PPT/RL (0.209)
3	PPT/ATL (0.197)	PPT/RL (0.154)	SPF/RL (0.270)	PPT/ATL (0.217)	PPT/RL (0.175)	PPT/ATL (0.202)	PPT/ATL (0.195)
4	SPF/RL (0.186)	SPF/RL (0.143)	PPT/AT L (0.211)	SPF/RL (0.205)	SPF/RL (0.156)	SPF/RL (0.180)	SPF/RL (0.188)

Abbreviations: RTL: Reinforced Thermoplastic Laminates; SPF: Semi-preg fabrics; PPT: Pre-preg tapes; ATL: Automated tape laying; RL: Robotic layup; Ther.: Thermoforming

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[1] 20% was used to vary the importance of the main criteria since it was reasoned that the subjective judgements between two experts in a specific field would not normally vary greater than this factor.
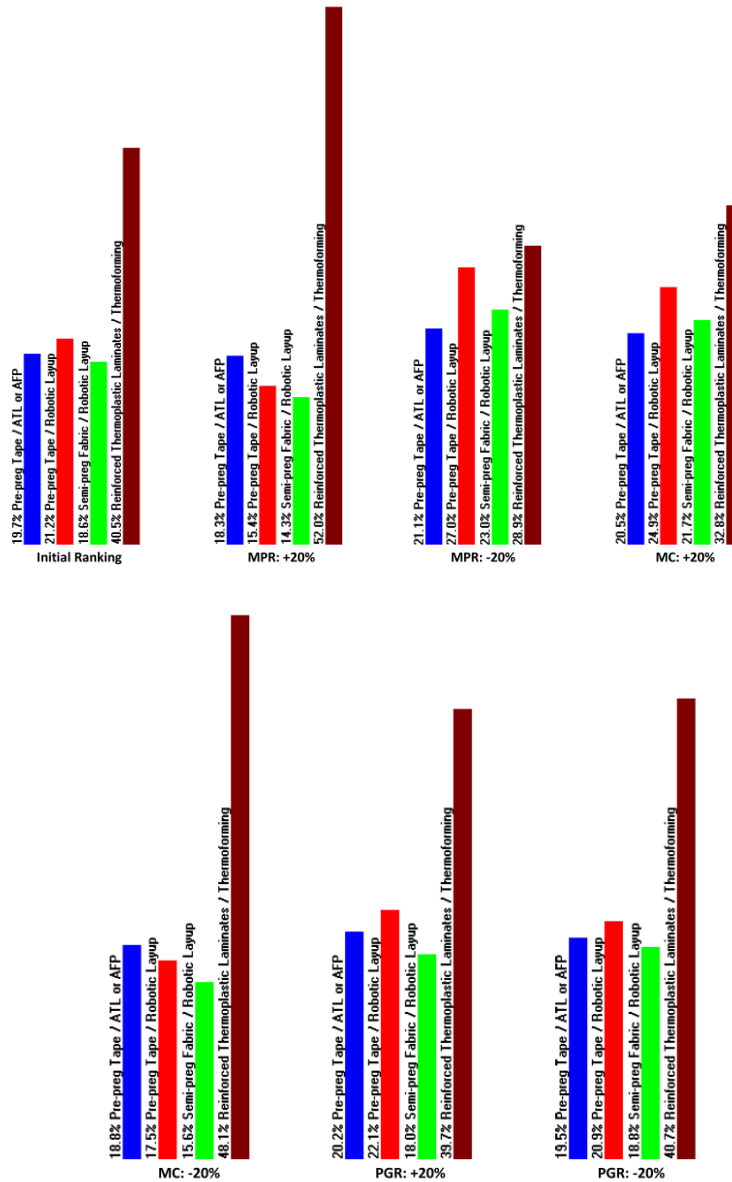
Figure 15: Sensitivity analysis results in graphical form.

The results in table 6 and figure 15 show that the rank of the manufacturing processes change slightly (relative to the initial ranking given in figure 14) as the priority values of the main criteria are varied. It is particularly observed that the semi-preg fabric/robotic layup, pre-preg tape/robotic layup and pre-preg tape/ATL processes interchange rank as the priority vectors of the main criteria are varied. However, the sensitivity analysis reveals that the rank of the first manufacturing process (i.e. reinforced thermoplastic laminates/thermoforming) does not change relative to the initial ranking. This indicates that the rank of this manufacturing process is robust against large changes in the weight of the main criteria and supports the outcome of the initial assessment that the most feasible manufacturing process is to use reinforced thermoplastic laminates in a thermoforming process.

4. Conceptual Design

4.1 Introduction

Chapter 3 describes the selection of the preferred process for the automated manufacture of a thermoplastic fibre-reinforced composite seat-pan. It was shown that the preferred process is to use reinforced thermoplastic laminate sheets in a thermoforming process. In this chapter, the conceptual design of a reconfigurable manufacturing cell, based on the thermoforming process, is presented.

The phases in the design life cycle of an RMS include (i) Architecture design (ii) Configuration design and (iii) Control Design (Bi et al., 2008). In the architecture design phase, the components and their interactions are determined. On a cell level, the components are the various machines, fixturing systems and material handling systems. In the configuration design phase, the most suitable arrangement and connections of machines under a given architecture is determined. Finally, in the control design phase, the control system is developed.

Therefore, this chapter serves, firstly, to develop the cell architecture in accordance with the functional requirements given in section 4.2. As a precursor to the configuration design, the chapter briefly describes the various models used to find representative cycle times for the purpose of evaluating the throughput rate of different configurations. With these models in hand, the chapter then develops and evaluates different configurations under the architecture developed previously. Evaluation criteria for the different configurations include capacity scalability and performance measures such as product throughput and machine utilization rates. The development of the control system and its architecture is described in chapter 6.

4.2 Cell Functional Requirements

In order to develop the architecture of the thermoforming cell, the functional requirements first need to be defined. Using figure 75 in Appendix B, which graphically illustrates the manufacturing stages that are required in a thermoforming process, and the product requirements of the seat pan outlined in section 3.2.1.2, the following requirements for an automated reconfigurable cell are derived and shown in figure 16:

  i. As pointed out in Appendix B, reinforced thermoplastic laminates are supplied in large sheets of 3660 mm × 1220 mm. Therefore, an automated cutting system is required to cut large laminate sheets into smaller laminates, called blanks, of the right shape and size.

  ii. As will be pointed out in section 4.3.2, biaxial tension needs to be applied to a blank in order to hold the sheet during heating and prevent wrinkling during forming. Therefore, a 'tensioning device', normally called a blank holder, is required.

  iii. It was pointed out in section 3.2.1.2 that some of the seat-pans used in commercial aircraft, that are located at emergency exit locations, need to be able to handle higher downward loads compared to those not located near

emergency exits. In order to handle these higher loads, these seat pans require reinforcements. Therefore, some means of applying reinforcements to a blank is required.

iv. Before a sheet can be formed into a target shape, the sheet must first be heated to its forming temperature. Therefore, an automated heating system is required.

v. An automated forming system is required which can form a blank into a target shape.

vi. An automated transport system, which can transport a blank or a blank holder through the stages outlined above, is required.

vii. For any automated system, ensuring the quality of a product manufactured by automated systems is of paramount importance. Therefore, quality assurance technologies need to be integrated at various points in the cell to ensure the quality of the product.
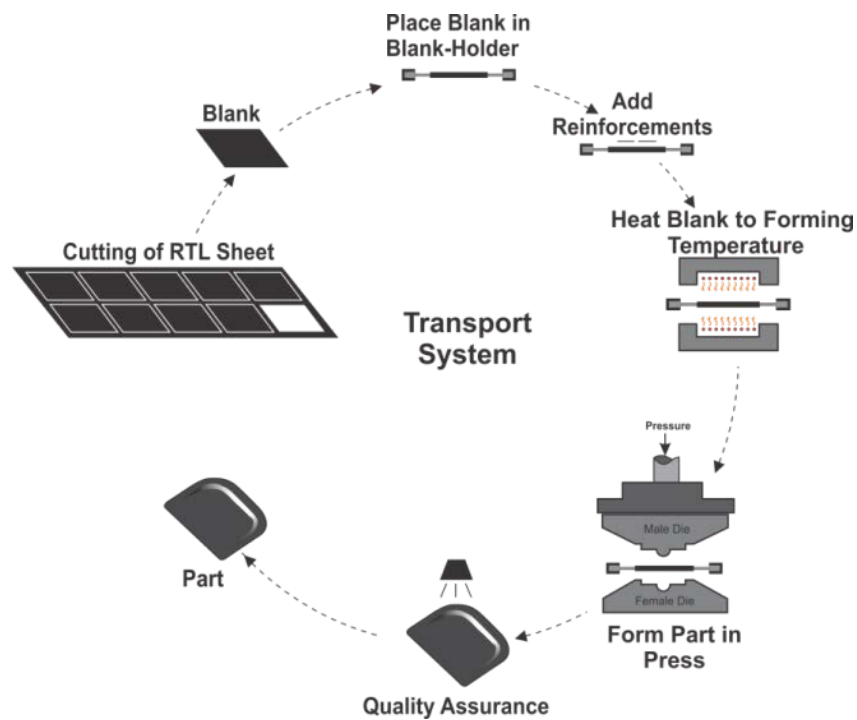
Figure 16: Cell Requirements for the manufacture of a seat pan.

4.3   Cell Architecture

As mentioned previously, the architecture design phase entails identifying the required machines, fixturing systems and material handling systems. Since the architecture specifically relates to the thermoforming process and the objective is to automate and incorporate reconfigurability into this process, automated technologies that support product variety and quick product changeovers in the thermoforming process will be investigated. Therefore, based on the functional requirements given in section 4.2, technologies relating to cutting, reinforcing, heating, forming, transportation and quality assurance will be investigated.

4.3.1   Sheet Cutting

As a general category of machining, cutting fibre-reinforced composite sheets can be performed using mechanical (direct-contact) methods or noncontact methods. In the former, high-speed steel (HSS), cemented carbide or polycrystalline diamond (PCD) cutting tools are mostly used (Negarestani, 2010). These tools are normally used in numerically controlled gantry-type machines such as shown in figure 17.
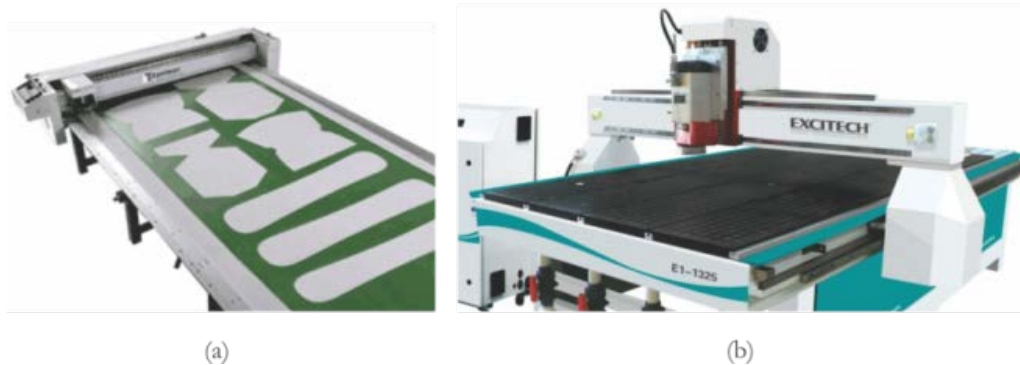
Figure 17: Examples of machines used to cut composite sheets: (a) Flatbed cutter (TextileWeb, 2014) (b) Planer machine (Exitech, 2014).

Mechanical cutting of fibre-reinforced composites is well established and understood and therefore is the dominant method used in industry (Teti, 2002). However, mechanical cutting methods are problematic due to the heterogeneous and anisotropic nature of the composite, the low thermal conductivity of the matrix and the abrasive nature of the fibres (Abrate & Walton, 1992). For example, the highly abrasive nature of fibres cause rapid tool wear which could, in turn, result in fibre pull-out, uncut fibres, delamination and micro-cracking at the edges. Further, since all polymer matrices have relatively low thermal conductivities compared to metals, heat can build up at the composite-tool interface which may lead to distortion or warping, induced thermal stresses or even unacceptable colour changes. As a result of these disadvantages, contactless cutting methods have received considerable attention as an alternative for cutting fibre-reinforced composites.

The methods for noncontact cutting of fibre-reinforced composites that are most mature include abrasive waterjet, electrical discharge, ultrasound and laser cutting. Laser cutting has shown to be technically superior and one of the most cost-effective approaches (Negarestani, 2010; Cenna & Mathew, 1997). In laser cutting, a high energy infrared beam is transmitted through lenses and focused on a small area which causes localized melting throughout the thickness of the composite. Some of the advantages laser cutting bring include minimum material wastage, quick set-up times, that no external tools are used (hence no wear or tool replacement is required), low heat input (hence there is a low risk of distorting or warping a part), and independence of the hardness of the part (Komanduri, 1997). However, one disadvantage of laser cutting is the slower cutting rates (~50-1400 mm/s) compared to mechanical cutting techniques (~2000-18000 mm/s).

The laser cutting process is very mature and has been extensively automated. Similar to mechanical cutting of composites, these automated systems are numerically controlled. This inherently supports product variety since a part of any shape and size can be cut. Due to the fact that no external cutting tool is required (and therefore no tool changes are required), the lead time for product changeovers in automated laser cutting systems is kept to a minimum.

4.3.2   Blank-holder

Complex material dependent deformation mechanisms occur within the sheet during forming of a reinforced thermoplastic laminate. If these deformation mechanisms are not properly controlled, undesirable wrinkling in the material may be induced.

One method to prevent wrinkling during forming is to use a blank holder. Conventional blank holders (figure 18) use springs that provides the necessary tension to prevent wrinkling of the material. These spring-based blank holders have the disadvantage that holes need to be drilled into the blank before forming. It has also been reported that set-up times can be as high as 4 hours (Alongi, 2004). These blank holders are also product-specific in that the springs have to be located at specific locations for every type of product and the frames on which the springs are located are fixed in size. This means a new frame has to be made for each type of product.
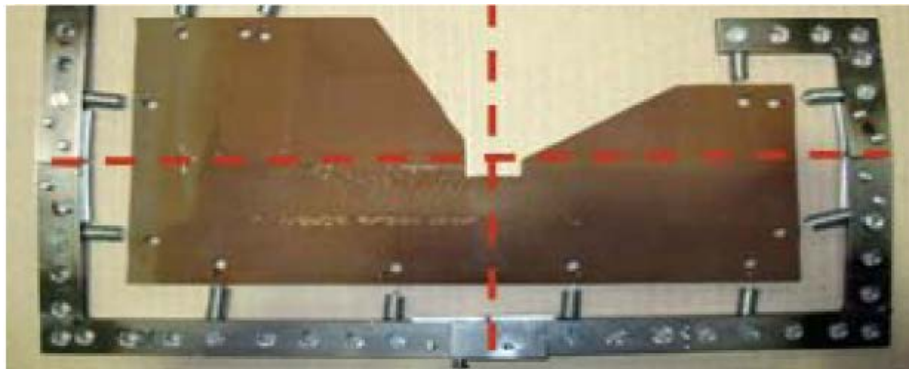
Figure 18: Spring-based blank holder used in press-forming reinforced thermoplastic laminates (Deterts et al., 2012).

In order to accommodate products with different sizes, blank holders based on adjustable frames (figure 19 (a)) and pneumatic clamps (figure 19 (b)) potentially offer an attractive solution. These clamp frames eliminate the need to replace the frame for every product and therefore also saves on storage space for storing clamp frames. These clamp frames reduce clamp set-up times, with set-up times as little as 5 minutes reported in the literature (Alongi, 2004).

As will be briefly motivated below, a central requirement of these clamp-based blank holders is that the clamping forces supplied by the pneumatic clamps will need to be adjustable in order to be able to accommodate a range of products with different material properties.
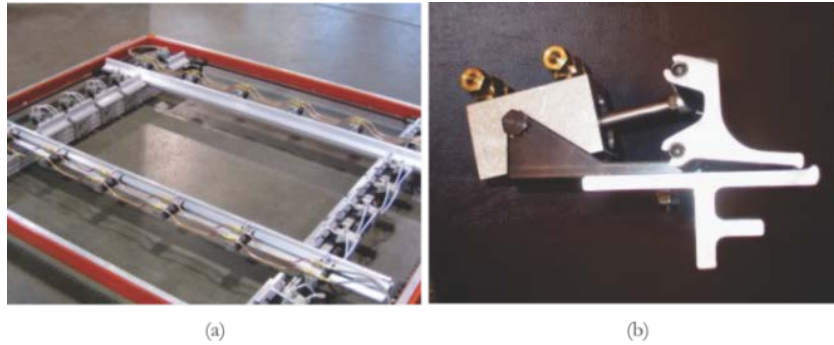
Figure 19: (a) Clamp-based blank holder, (b) Pneumatic clamps (MAAC Machinery Corporation, 2014).

During press-forming of complex, doubly curved shapes using thermoplastic fibre-reinforced sheets, various forming mechanisms must occur to facilitate part manufacture. Apart from resin percolation of the matrix amongst the fibres and transverse fibre flow, two important forming mechanisms are intra-ply shear and inter-ply slip. Intra-ply shear for fabric, where the reinforcing fibres are normally in a minimum of two directions, takes the form of the in-plane trellis effect (figure 20). The trellis effect occurs in all complex curved shapes when manufactured using fabrics.
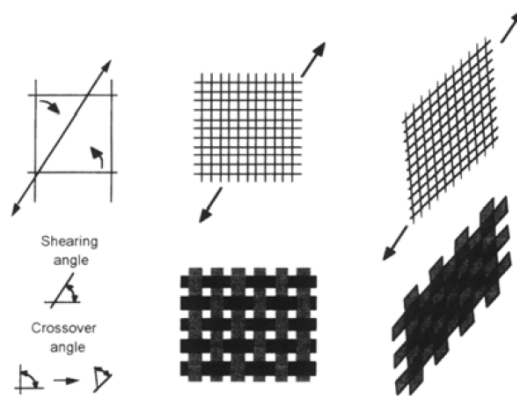
Figure 20: Intra-ply shear mechanism (trellis effect) in fabrics (Murtagh, 1997).

When the in-plane shearing force acts at an angle relative to the orthogonal fibres, the angles between these fibres decrease as shown in figure 20. The angle between the fibres can decrease only a finite amount until they are locked. This locking angle is depended mainly on the weave style of the fabric and the thickness of the fibres. Attempting to reduce the angle by increasing the shearing force will induce out-of-plane buckling, causing wrinkles in the formed part.

Inter-ply slip is the process where individual plies move relative to one another (figure 21), and is caused by the inextensibility of the reinforcing fibres. For example, when a part is formed with a 90° bend, the inner plies will undergo a compressive stress while the outer plies will undergo a tensile stress. If no slip is induced between the layers, then out-of-plane fibre buckling occurs causing wrinkles in the formed part as shown in figure 22 (a).
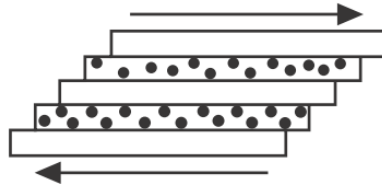
Figure 21: Inter-ply slip mechanism (Mallick, 2007).
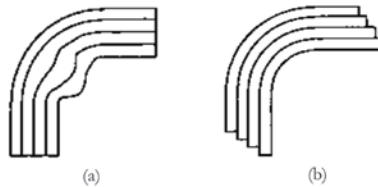
Figure 22: Inter-ply-slip in a 90°bend (Murtagh, 1997). (a) No inter-ply slip causes fibre buckling. (b) Inter-ply slip is induced and therefore no fibre buckling is caused.

In-plane shearing stresses are controlled by the friction force of the clamping frames discussed earlier. This friction force needs to be large enough to induce both intra-ply shear and inter-ply slip, while simultaneously being small enough to not exceed the locking angle in the case of intra-ply shear or inhibit ply slip in the case of inter-ply slip, which will lead to fibre buckling and wrinkling. The shearing stress naturally also needs to be smaller than the tensile stress of the fibres in order to prevent fibre elongation or breakage. The shearing stress that induces intra-ply shear and inter-ply slip is a strong function of the material properties (for example resin, reinforcements, type of weave and number of plies). Since the shearing force is induced by the friction force of the clamping frame, the pneumatic clamping forces need to be varied when the clamping frame is used to form a variety of products with different material properties. The ability to vary the clamp force will allow the clamping frame to be reconfigured for optimal forming conditions when product changes occur.

As discussed earlier, the clamping pressure required to prevent wrinkling during forming of a part is a strong function of the material that is used to make the part. Limited research has been conducted to relate the clamping pressure during forming of different thermoplastic composite materials.

Lim *et al.* (1999) investigated the effects of forming conditions (including blank-holder force, the blank size and the tool geometry) on the formability of knitted Kevlar reinforced polypropylene (PP) sheets. They concluded that the magnitude of the blank holder force is one of the indispensible factors for the successful forming of thermoplastic fibre-reinforce parts. Ji Seok *et al.* (2007) investigated the effect the blank holder force has on the forming behaviour of non-crimp fabrics with chain stitches. They showed that defects such as in-plane and out-of-plane buckling were reduced with an increase in blank-holder force. However, too large blank holder forces caused severe shear deformations. They concluded that the optimization of the blank holder force will minimise wrinkling during the forming process. Wilks (2000) studied the effect of temperature, blank holder force and stamping velocity on the formability of polypropylene based composites. Wilks (2000) noted that with a low blank holder pressure of 0.05 MPa, the material pulled through the clamping jaw

prematurely, which subsequently led to wrinkling, while a high clamping pressure of 1.1 MPa led to fibre breakage. Hou (1996) and Friedrich *et al.* (1997) investigated the effect the blank holder pressure has on the forming of a hemispherical part using polyetherimide (PEI) laminate sheets reinforced with continuous woven glass-fibre fabric. They showed that a clamping pressure of 0.1 MPa was insufficient to induce intra-ply shear throughout the laminate during forming which led to wrinkling. They subsequently showed that by increasing the clamping pressure to 0.2 MPa only little wrinkling was visible while 0.3 MPa yielded no wrinkling in the formed part.

As is evident from above, the clamping pressure is a very important aspect when using clamp-based blank holders. From a reconfigurability perspective, these blank holders are highly favourable since they allow quick product changeovers and support product variety.

4.3.3   Reinforcing

The placement of reinforcements onto reinforced thermoplastic laminates is still an active area of research, especially in the field of automation. The placement process is currently applied either as a pre-heating step or as a post-forming step in the processing chain for the manufacture of thermoplastic composite parts. However, there are certain concerns that need to be addressed in both of these routes.

For the application of reinforcement as a pre-heating step, unidirectional thermoplastic tapes are first welded onto a laminate after which the reinforced laminate is heated and then pressed into the target shape. This welding process is relatively straight forward since the laminate is flat. The interfacial properties between the tape and the laminate are usually not a concern since the tape will be fully consolidated onto the laminate in the forming stage. However, a concern associated with this process is the displacement of reinforcements both within the heating and forming stages. This is especially true if the end-product is geometrically very complex. Since reinforcements are usually strategically placed to optimize the strength of a part in a particular area, displacement of these reinforcements are unacceptable. However, as pointed out in Appendix B, some research has been conducted (Grouve et al., 2012; Bersee et al., 2006) in which this concern was addressed. It should be pointed out, however, that this research was conducted as single experiments and further research needs to be conducted in order to verify its success in series production.

For the application of reinforcements as a post-forming step, unidirectional tapes are welded onto the part after it has been formed. This process can be complex since the tape placement needs to be performed onto a contoured part. What makes this process so difficult is not only the complex automation required to lay down tapes onto a contoured surface, but finding and controlling the optimal process parameters of the welding process can be problematic. This is because the process parameters of the welding process are a strong function of the properties of the thermoplastic material. Therefore, a special concern associated with this process is the quality of the interfacial properties of the welded region, such as the fracture toughness of the weld, between the unidirectional tapes and the part.

Both the pre-heating and post-forming routes for adding reinforcements can be performed using the tape placement technologies discussed in section Appendix B. In that section, the use of six-degree-of-freedom robots with specialized tape placement heads for manufacturing parts from unidirectional tapes was reviewed. These robots, with their specialized end-effectors, are very flexible and can be quickly reconfigured to lay down any shape, size or thickness of reinforcements a part may require. The lead time for changing the reinforcing material depends primarily on the tape placement head. Most of the placement heads developed thus far can store a number of different tapes, both with regard to the geometry and type of material, on spools mounted directly on the tape placement head to reduce this lead time.

4.3.4 Heating

Heating of reinforced thermoplastic laminate sheets are mostly performed in electric radiant heaters (figure 23) in which the temperature of the heating elements are controlled by independent controllers in either an open-loop or closed-loop fashion.

When a heater is controlled open-loop, the sheet is heated for a predetermined time and neither the sheet temperature nor the temperatures of the heating elements are measured during heating. Using this approach, the temperatures of the heating elements are maintained at a pre-set temperature by controlling the voltage supplied to the heating elements by rheostats or variacs. This approach, which is often used in industry, represents one of the biggest contributors to lead times during product changeovers, because finding and setting the optimal heater temperature is done in a trial-and-error fashion.

Figure 23: Heaters used for heating reinforced thermoplastic sheets (PreWired, 2014; North Sea Plastics, 2014).

Alternatively, when the heater is controlled closed loop, the heater temperature is adjusted in response to the measured sheet temperature. The sheet temperature is usually measured with an infrared sensor, such as a pyrometer. Since the optimal forming temperature for a specific material is usually provided by material suppliers, only the sheet temperature has to be specified to the controller of the heater which will automatically adjust the temperatures of the heater elements to heat the sheet to the right temperature. Therefore, using this closed-loop approach, lead times between product changeovers are significantly reduced.

Since the temperatures of heating units are easily adjusted, whether they are controlled open-loop or closed loop, according to the required melting temperature of a specific material, product variants are easily accommodated.

4.3.5   Forming

Forming of reinforced thermoplastic laminate sheets is mostly done in a hydraulic press. The part is positioned between an upper die, which is attached to the ram of the press, and a lower die, which is attached to the base. When the part is in position, the ram is released in order to form the part under pressure between the two die halves.

A Conventional die tool used in press forming is a prime example of a dedicated tool usually fabricated for a specific part only. A die tool is normally fabricated from a tool-steel billet which is costly and can take days, weeks or even months to fabricate. For example, the design and production of the complex dies used for interior components of an automobile may cost up to R5 million and may require 6 to 9 months to fabricate (Koc & Thangaswamy, 2011). A whole new tool needs to be fabricated for each new product.

In order to decrease tooling costs and the lead-time between product changeovers, reconfigurable discrete dies potentially offer a solution. The discrete die concept (figure 24) has received significant attention from researchers (Friedrich & Hou, 1998; Koc & Thangaswamy, 2011; Kleespies & Crawford, 1998; Haas et al., 2002; Walczyk et al., 1998; Kelkar et al., 2005) with their focus ranging from the development of the hardware to the development of the control software. The discrete dies developed by these researchers are all fairly similar in that they all comprise a matrix or bed of individually actuated, closely-packed, pins and an elastic rubber interpolator sheet which spans across the pins in order to provide a more smooth forming surface.
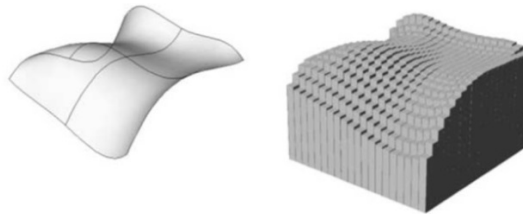
Figure 24: Approximating a mould surface using a discrete die pins (Kelkar et al., 2005).

The discrete die concept has shown to be viable, but it is inherently limited with respect to the surface quality and amount of detail achievable from the finite number of pins.

Another innovative concept often used in the injection moulding industry, which may also significantly reduce costs associated with tooling and the lead time between product changeovers, is to segment a die tool such that it has modular interfaces (figure 25). This will allow smaller tools, called inserts, to be added, removed or interchanged in order to accommodate product variants.
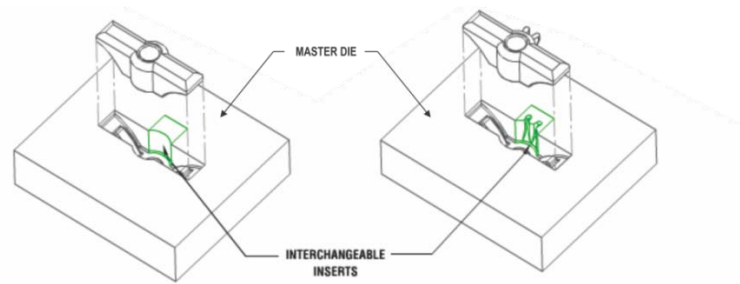
Figure 25: Die with interchangeable inserts (Adapted from Kinetics (2014)).

There are various challenges that need to be addressed when using such a concept. For example, to ensure that the die tool does not deform under pressure, which could cause distortion in the part, the modular die should be designed such that sufficient stiffness of the die is ensured. Close tolerances should also be ensured between the modular tool and inserts to ensure that pressure is applied homogenously over the part being formed. Thermal effects such as the rate of thermal expansion between the inserts should also be considered. In order to avoid residual stresses and dimensional inaccuracies, the rate of thermal expansion between all the tool parts and the product being formed should also be similar. In order to automate changeover of the inserts, and thereby reducing the lead time between product changeovers, this modular tool concept can be complemented with an automatic tool changing device.

Despite the innovative concepts discussed above, the achievable quality, both in terms of surface finish and accuracy remains questionable. An alternative approach, which has been extensively developed in industry (Roemheld, 2014; Forwell, 2014; EAS, 2014) to reduce the lead times between product changeovers, is to use a Quick Die Change (QDC) system (figure 26).
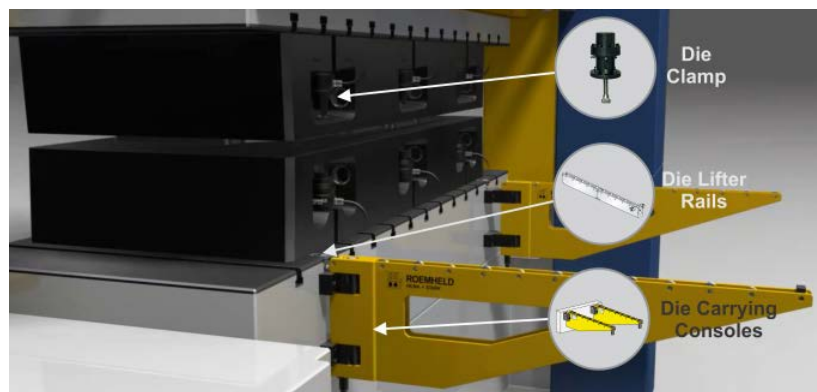
Figure 26: Quick Die Change (QDC) system (Adapted from Roemheld (2014)).

QDC systems include infrastructure for loading, positioning and securing dies. Loading of dies in a press is facilitated by die carrying consoles as shown in figure 26. In order to make it easy to push and pull the die into and out of the press, these consoles use hardened cylindrical rollers. The die is usually placed on a console using a forklift and the die is then either pushed in manually or by a hydraulic lever.

Positioning of dies within a press is achieved using die lifter rails. These rails are installed within the T- or U-slots of the base as shown in figure 26. Spring, hydraulic or pneumatically actuated roller bearings, cylindrical rollers or balls are usually used in these rails to lift the die a small distance to permit movement and positioning of the die in the press.

To secure the upper and lower dies to the ram and base, die clamps are used as shown in figure 26. A comprehensive range of clamp designs are available which can be manually, hydraulically or magnetically actuated. These clamps can either be embedded into the ram and base or can be externally retrofitted.

Other infrastructure provided by companies offering QDC systems include die transport and storage systems. Transportation systems for dies range from general solutions, such as forklifts, to more customized solutions, such as die change cars or rail-guided transport systems. Similarly, storage systems can range from simple and general roller beds to more complex and customized storage systems which, for example, can pre-heat a die in order to further reduce the lead time caused by die changeovers.

4.3.6 Transport System

The handling of reinforced thermoplastic laminates in the thermoforming process is almost exclusively done by hand. The process starts of by manually picking a large sheet from a buffer and placing it onto a cutting machine that will cut the sheet into smaller blanks of the right shape and size. These blanks are then manually collected and stored in a buffer. In the next step, the blanks are again manually picked from the buffer and placed into a blank holder. If a spring-based blank holder is used, holes first need to be drilled at specific locations as described in 4.3.2. In most thermoforming processes, a heater is next to and in-line with a press. In this setup, a shuttling system (figure 27) is used to transport the blank holder between the heater and the press. Once the part has been processed at this station, the part is removed manually from the blank holder and stored in a buffer for further processing.
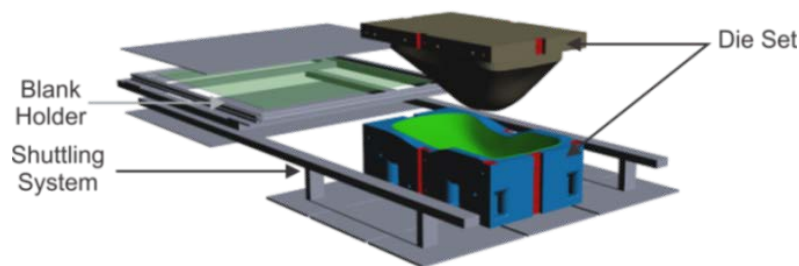
Figure 27: Shuttling system used to transport a blank in a blank holder between a heater and a press (Sirris Leuven-gent Composites Application Lab, 2014).

The manual handling process described above is very reconfigurable due to the flexibility of humans, but the process can be slow, prone to errors and may result in damage to the raw material. In order reduce these risks, but maintain the flexibility, an automated reconfigurable transport system for handling the material through all manufacturing stages is required.

Conveyor systems offer an attractive and efficient way to transport material in a manufacturing process. Since modularity is an important aspect for reconfigurability as described in section 2.2.2.1, modular conveyor systems potentially offer an attractive automated and reconfigurable solution for transporting reinforced thermoplastic laminate sheets in a thermoforming process.

Several conveyors systems based on modular construction are available in industry. For example, Bosch Rexroth (2014) offer a wide range of Transfer System (TS) conveyors that uses modular components such as corner modules, guides, lift-transfer units, pallets, etc. (figure 28). This allows the end-user not only to tailor the conveyor's configuration depending on the manufacturing requirements, but also allows the user to quickly change the configuration (figure 28 (b)) once these requirements change.
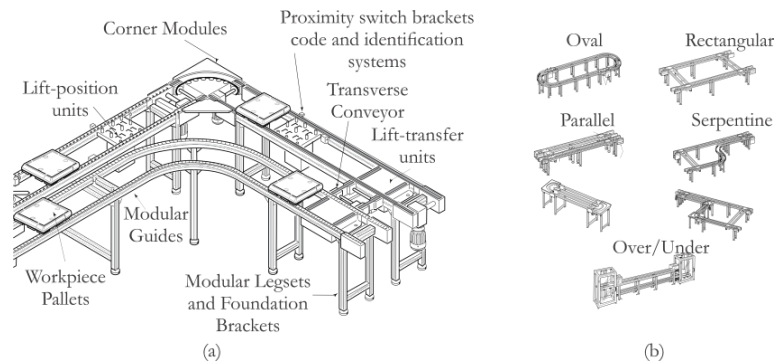
Figure 28: Modular conveyor components can build a wide range of different transport configurations (Adapted from Bosch Rexroth (2014)).

An essential component of the TS conveyor is the workpiece pallet (figure 29). Ranging from 160 × 160 mm to 1040 × 1040 mm in size, the pallets provide modular surfaces so that the pallet can be tooled with a customised fixture for securing parts. The pallet also allows identification and data storage modules, such as radio frequency identification (RFID), to be mounted to the pallet. This enables data relating to the part to accompany the part as it travels along the conveyor. This information can be accessed by RFID tag readers along the conveyor to control the routing of the pallet on the conveyor.
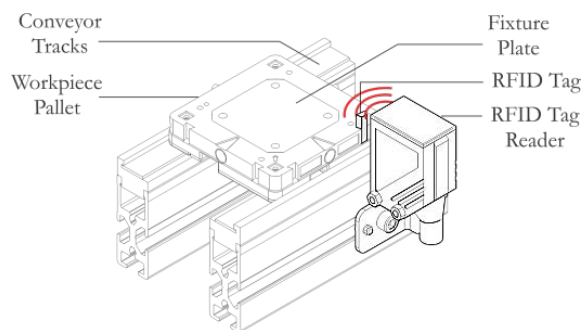
Figure 29: Conveyor Pallet with fixture plate and RFID system Adapted from Bosch Rexroth (2014).

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The modular granularity of the TS conveyor systems is very small, giving the user a wide range of possibilities to design and customize the system according to the manufacturing requirements. However, one disadvantage this may pose is that if a new configuration is required (for example to accommodate a new machine), the lead time to extend or change the configuration may be very high. Lanco (2014) potentially addressed this problem by making the modular entities larger.

Modular conveyors are useful systems that allow the efficient transport of materials through the manufacturing workspace. However, changing the path along which material flow requires physically altering the conveyor through removal or addition of modules. This can be expensive and time consuming. A system that is often used for the transport of material in a manufacturing workspace (cell) and which is able to quickly adapt the path along which it routes material is the industrial six-degree-of-freedom robot.

The essential features of industrial robots are their inherent versatility due to their articulated nature, their control flexibility and modular nature endowed by their end-effectors. As a result, these robots can be quickly adapted to perform a range of tasks in a multitude of ways.

There are numerous modular end-effector tools available which enable a robot to pick up and transport a flat or contoured part. For example, Schmalz (2014) has designed a modular vacuum gripper (figure 30 (a)) for transporting flat or complex shaped products. These vacuum end effectors can be quickly adapted by changing, adding or removing suction pads according to the size, shape and complexity of the product that needs to be transported.

There are also modular systems available that enable the robot to change its end-effector tool quickly in response to product changeovers. One system that enables the automatic and quick change of the end effector tool has been designed by Destaco (2014) (figure 30 (b)). These modular, quick tool changers have utilities available to quickly interface an end-effector tool with I/O's, air, water, servo power and vacuum lines.
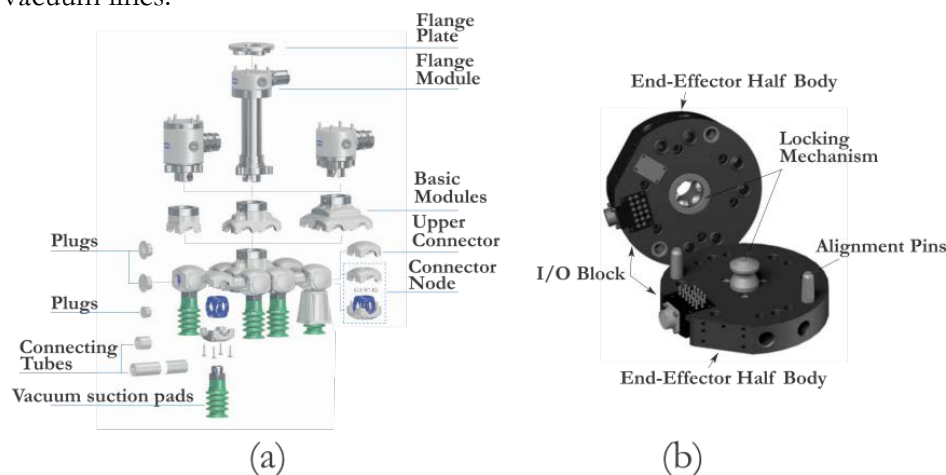
Figure 30: (a) Modular vacuum end-effector (Adapted from Schmalz (2014)) (b) Automatic tool changer (Adapted from Destaco (2014)).

4.3.7   Quality Assurance

The quality of a composite part is defined by several factors, such as its mechanical properties and surface aesthetics. Since stringent requirements are usually placed on composites in terms of these properties, especially in the aerospace industry, quality assurance forms an indispensible part of the manufacturing process for composite parts.

As shown in figure 31, typical defects found in composite parts made from laminated materials include delaminations, cracking, voids, porosities, inclusions, fibre breakage, fibre wrinkling and fibre misalignment (Hsu, 2008). These defects can be detected through either destructive (mechanical) or non-destructive tests. In destructive testing, the mechanical properties of a part, such as its tensile, compressive, shear, flexural and toughness properties, are measured to determine if there are defects in the part by physically altering the part. However, it is sometimes not desirable or feasible to carry out destructive tests on finished parts. Therefore, non-destructive tests have become a popular means of quality assurance in the composites industry.
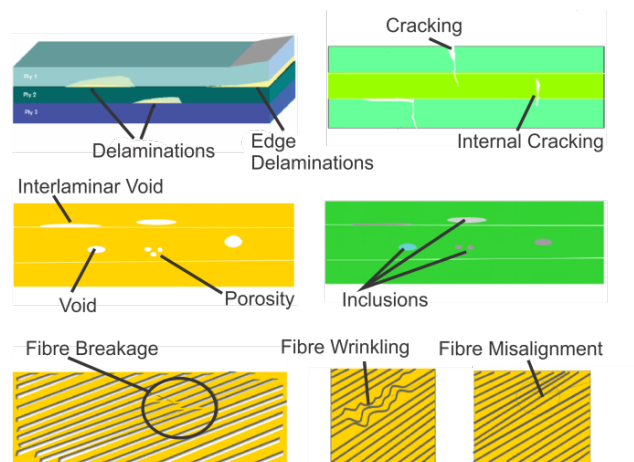
Figure 31: Typical defects in composites made from laminate materials (Adapted from Air Washington (2014)).

In non-destructive testing, some sensor or instrument is used to evaluate various properties of or check for defects in a part without damaging or altering the part. The most common non-destructive testing methods used in the composites industry can be grouped into radiographic, ultrasonic, acoustic, thermographic and vibrational methods. Although ultrasonic testing is the most commonly used method for detecting defects, no single method can be used to detect all defects (Zoghi, 2014).

Non-destructive testing of composite parts in industry is mostly done manually by trained personnel (figure 32 (a)). This is usually a laborious and time consuming task and successful testing of parts depends heavily on the training, experience and integrity of these personnel. It is generally necessary that personnel conducting non-destructive tests undergo extensive training (Non-Destructive Academy of South Africa, 2014) which could be very expensive. Therefore, automating non-destructive testing has become one of the strategic objectives for many companies in the composites industry.

Figure 32: (a) Manual and (b) automated non-destructive testing of composite parts (Olympus, 2014; Apodius, 2014).

Automating the non-destructive testing of parts (figure 32 (b)) can potentially increase the speed and reliability of testing a part while decreasing the associated time and costs. Despite these possible advantages, the adoption of automation for non-destructive testing, both in research and industry, has been limited (Bogue, 2010).

The automation of non-destructive testing in the composites industry has primarily been focused on developing robotic systems for large structures, such as aircraft wings and fuselages, with relatively flat or geometrically noncomplex curvatures. Examples include climbing robots using suction cups (Shang et al., 2007) and autonomous robotic vehicles (Dobie et al., 2011). Although these robotic systems have been successfully implemented, they could only cope with simply curved structures and testing was only performed after the part was manufactured. Therefore, some researchers and industry have focused their efforts on finding ways to automate the testing of smaller and geometrically complex parts within the manufacturing stage.

Research in the non-destructive testing of composite parts in the manufacturing stage has shown that, as a result of their flexible nature, articulated robots (figure 32 (b)) are ideally suited for the testing of smaller components with complex curvatures (Mineo et al., 2012; Haase et al., 2014). The suitability of the robots is derived from their inherent versatility which enables the robot to follow complex paths (contours) during the testing of a part. These paths can be quickly adapted through automated tool-path generation methods (made possible by CAD/CAM software packages such Delcam (Delcam, 2014) and Robotmaster (Robotmaster, 2014)) which decrease lead times between product changeovers. Further, since the specific testing method used depends on several factors, such as the raw material of the part, the apparatus used for testing needs to be changed. This apparatus, which is located on the end-effector of the robot, can be easily interchanged. Therefore, product variety is easily supported.

4.4   Cycle Time Analysis

As shown on the temperature and pressure versus time graph of figure 33, two key phases are required for thermoforming an RTL sheet, namely a heating phase and a press-forming phase. In the heating phase, the sheet is heated from room temperature T_{rt} to a temperature T_{max}, which is above the melting temperature T_m of the thermoplastic matrix. The sheet is usually heated to T_{max} to account for the heat lost when the sheet is transported between the heating and forming stations. In the press-forming stage, the sheet is formed to the required shape in a press and cooled to a temperature T_d where the part is dimensionally stable and has sufficient stiffness to be extracted and handled.
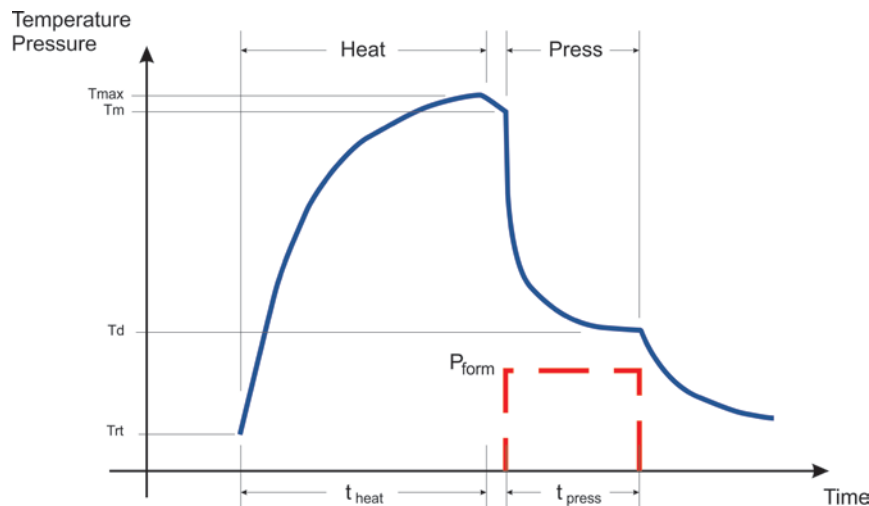
Figure 33: Non-isothermal thermoforming cycle for thermoplastic FRC sheets.

For the purpose of obtaining representative times for the heating and forming phases of the seat pan, the following sub-sections describe the heating and cooling models, respectively, that were used. Since reinforcements are required in the current study, a model for the reinforcement time is also described. It should be noted that the cycle times for cutting and quality assurance are not included here since the former is expected to be much faster than the other stages, while for the latter case significant research still has to be conducted on this aspect. The cycle times obtained from these models will be used to evaluate different cell configurations for the manufacture of the seat pan.

4.4.1   Heating Time

There are three ways heat can be transferred between two objects at different temperatures: conduction, convection and radiation heat transfer. Conduction is heat transfer through a solid or stationary liquid; convection is heat transfer caused by the movement of liquids while radiation is electromagnetic energy interchange between an energy source and an energy sink.

It is often convenient to neglect one or two modes of heat transfer without sacrificing too much accuracy in order to simplify a heat transfer problem. An

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important relationship that determines the relative importance of convection heat transfer to conduction is the dimensionless Biot Number:

$$Bi = \frac{hL_c}{k}$$

(4.1)

where h is the convection heat transfer coefficient of the surrounding fluid, L_c is the characteristic length of the object defined as $L_c = V/A_s$ (V is the volume and A_s is the surface area) and k is the thermal conductivity of the object. It is generally accepted (Cengel & Ghajar, 2011) that if $Bi \leq 0.1$ then an object has a small resistance to heat conduction (meaning there are small temperature gradients throughout the body) and therefore heat conduction can reasonably be neglected.

Considering the RTL sheets, a small Biot number occurs if either the heat transfer coefficient or sheet thickness is very small, or the sheet thermal conductivity of the sheet is very large or a combination of these are in effect. If polyetherimide ($k \cong 0.22\ W/m \cdot K$) is used as the resin for the RTL sheet of thickness 1 mm and it is assumed that the sheet is heated in natural convection air ($h \cong 10\ W/m^2 \cdot K$) then $Bi = 0.045$. Therefore, it can reasonably be assumed that temperature gradients within the sheet are negligible and thus heat transfer by conduction can be neglected without sacrificing too much accuracy.

Further, when comparing the heat transfer contributed by convection to radiation, it is often observed that heat transferred by radiation is typically ten times that of heat transferred by convection (Throne, 1996). This can be attributed to the fact that heat transferred by radiation is proportional to the fourth power of the temperature difference between two objects while the heat transferred by convection is only proportional to the first power of the temperature difference. Therefore, as a first approximation, only heat transfer by radiation will be used to calculate the heating times for the RTL sheets.

In order to calculate a representative heating time, we start with an energy balance between the radiant energy into the sheet and the change in internal energy of the sheet:

$$Q_{rad,in} = \Delta U$$

(4.2)

where the change in internal energy can be expressed as $\Delta U = mc_p \Delta T_{sheet}$ where m is the mass of the sheet, c_p is the specific heat of the sheet and ΔT_{sheet} is the difference between the final and initial sheet temperatures. By dividing both sides by time and the surface area, we obtain equation 4.3 which contains an expression for the rate of radiation heat transfer to the sheet:

$$\dot{q}_{rad} = \frac{\frac{m}{A_s} c_p \Delta T_{sheet}}{\Delta t}$$

(4.3)

Rearranging equation 4.3, an expression for the time required to heat the sheet is obtained:

$$\Delta t = \frac{\frac{m}{A_s} c_p \Delta T_{sheet}}{\dot{q}_{rad}} \qquad (4.4)$$

The net radiation heat transfer rate from the heater to the sheet, $\dot{q}_{rad}$, is calculated from the Stefan-Boltzmann law:

$$\dot{q}_{rad} = \sigma \epsilon_{eff} F (T_{heater}^{\,4} - T_{sheet,ave}^{\,4}) \qquad (4.5)$$

where $\sigma = 5.670 \times 10^{-8} \frac{W}{m^2 K^4}$ is the Stefan-Boltzmann constant, ϵ_{eff} is the effective emissivity of the heater and the sheet which is defined as:

$$\epsilon_{eff} = \frac{1}{\frac{1}{\epsilon_{heater}} + \frac{1}{\epsilon_{sheet}} - 1} \qquad (4.6)$$

and F is the view factor which quantifies the percentage of the radiant energy that leaves the heater that is intercepted by the sheet. F is easily obtained from figure 34.
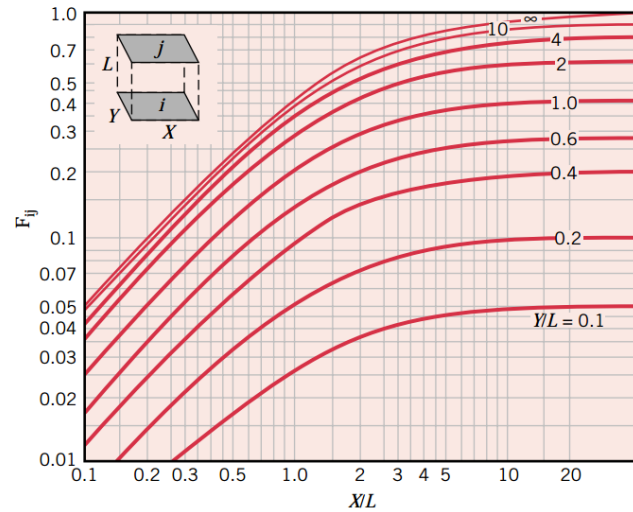
Figure 34: View Factors for aligned parallel planes (Incropera et al., 2007).

It must be noted that the emitted radiation is a function of the wavelength, λ, and any polymer has a specific range in which radiation is absorbed most. Since equation 4.5 represents the total radiation emitted at all wavelengths, it has to be adapted to take into account only the amount of radiation that is absorbed efficiently by the sheet. Therefore, it is important to match the radiant source's (heater) peak wavelength to the primary absorption wavelengths of the polymer.

For the case of polyetherimide, figure 35 shows that peak absorption bands lie approximately in the 3.3 μm to 3.5 μm and 5.7 μm to 8 μm ranges. For maximum efficiency, the peak wavelength of the heater should be within these ranges. Using 3.4 μm, Wien's displacement law can be used to determine the required temperature of the heater (Cengel & Ghajar, 2011):

$$\lambda T_{heater} = 2897.8 \ \mu m \cdot K \qquad (4.7)$$
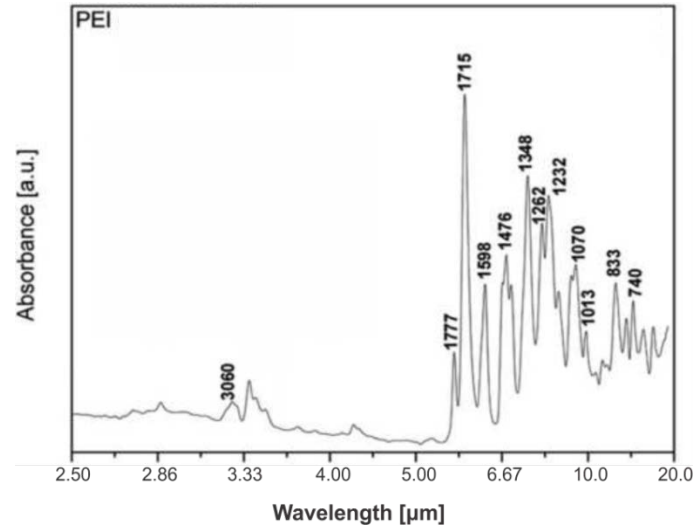
Figure 35: FTIR spectrum for Polyetherimide (Adapted from Amancio-Filho et al. (2008)).

Therefore, a temperature of approximately $866\,\text{K} \cong 1100\,°\text{F}$ for the heater will have a peak wavelength of $3.4\,\mu m$ which will match the peak absorption range of polyetherimide. Lastly, we need to determine what percentage of the radiated energy of the heater will actually be absorbed corresponding to the aforementioned wavelength ranges. Using figure 36, it is observed that the percentage of energy corresponding to wavelengths less than $3.3\,\mu m$ is 26% while the percentage of energy corresponding to wavelengths less than $3.5\,\mu m$ is 29%. Therefore, the net energy absorbed in the $3.3\,\mu m$ to $3.5\,\mu m$ band is 3%. Similarly, the percentage of energy corresponding to wavelengths less than $5.7\,\mu m$ is 61% while the percentage of energy corresponding to wavelengths less than $8\,\mu m$ is 78%. This means the net energy absorbed in the $5.7\,\mu m$ to $8\,\mu m$ band is 17%. Summing the energy absorbed in the two bands means that the total energy absorbed efficiently by the sheet is actually only 20% of the incident radiation emitted from the heater. Therefore, equation 4.8 is the final expression that is used to calculate a representative time to heat a sheet[2]:

$$\Delta t_h = \frac{\frac{m}{A_s} c_p (T_{sheet,final} - T_{sheet,init})}{2\,\beta \cdot \epsilon_{eff} F (T_{heater}{}^4 - T_{sheet,ave}{}^4)} \tag{4.8}$$

where β is the factor that quantifies the actual percentage of energy absorbed by the sheet.

Using data freely available for polyetherimide, equation 4.6 and figure 34, a representative time required to heat the sheet is

$$\Delta t = \frac{1.83 \times 1100 \times (584 - 297)}{2 \times \sigma \times 0.2 \times 0.81 \times 0.56 \times (866^4 - 440^4)} \cong 114\ \text{sec}$$

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[2] Since the sheet is heated from both sides, the denominator of equation 4.8 is multiplied by 2.
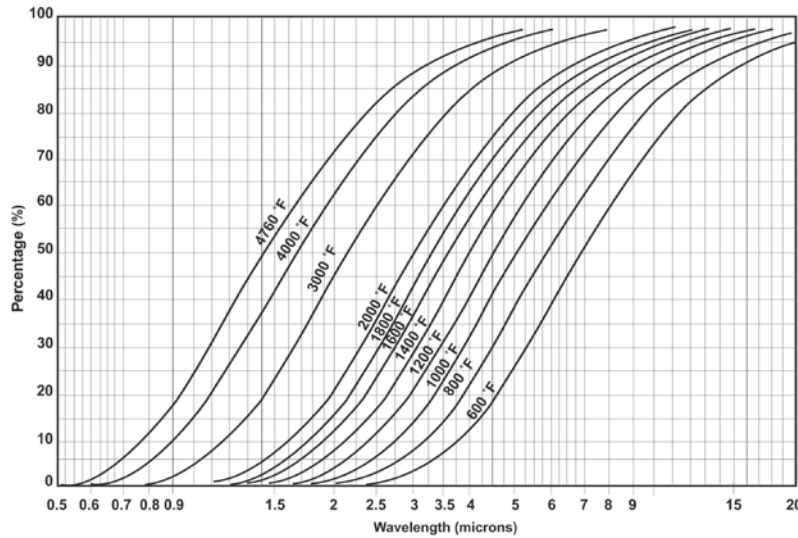
Figure 36: Percentage of radiant energy that is at shorter wavelengths than a specific value wavelength for heaters of a given blackbody temperature (Adapted from Watlow (1997)).

4.4.2   Forming Time

In the case of a sheet cooling between two metallic dies, conduction is considered the primary mode of heat transfer while convection is considered insignificant due to the very high thermal conductivities of die materials. Radiation is also considered negligible once the sheet is in contact between the dies.

By considering only conduction and taking into account only the thermal resistance at the interface between the die and the pressed material[3], Dewhurst & Blum (1989) showed that the cooling time can be represented by the simple equation:

$$\Delta t_c = -\frac{\rho L c_p}{h} \ln \left[\frac{T_e - T_m}{T_i - T_m} \right] \qquad (4.9)$$

where ρ is the density of the product material, L half thickness of the product material, c_p is the specific heat of the product material, h is thermal contact conductance between the sheet and die material, T_e is the demoulding temperature of the product material, T_m is the die temperature and T_i is the is the initial temperature of the product material.

Ding & Wang (2012) studied the effects of the interface contact pressure and mean interface temperature on the thermal contact conductance across stainless steel and glass fibre reinforced plastics during thermoforming[4]. They showed that the thermal contact conductance increases with increasing interface contact pressure while it

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[3] Dewhurst & Blum (1989) showed that the thermal resistances of the product material and the die material can safely be ignored without losing too much accuracy.

[4] This data is considered due to a lack of other data and it is assumed the properties of stainless-steel are sufficiently close to tool steel (mostly used for dies) for a first approximation.

decreases with increasing mean interface temperature. Their research produced two models which predict the thermal contact conductance under various interface pressures and mean temperatures. In order to obtain a representative coefficient, it was decided to use the former model:

$$h = 18.6473 \times P^{0.38447} \tag{4.10}$$

Using this model for the interface contact conductance, freely available data on polyetherimide, typical forming conditions[5] and a product thickness of ~ 1 mm, a representative cooling time is calculated as:

$$\Delta t_c = -\frac{1910 \times 0.5(10^{-3}) \times 2000}{18.6473 \times 2^{0.38447}} \ln \left[\frac{170 - 80}{270 - 800} \right] \cong 59 \text{ sec}$$

4.4.3 Reinforcing Time

The time required to place unidirectional fibre-reinforced thermoplastic tapes is a function of many variables, some of which are often difficult to quantify. One of these, the shape complexity, has received considerable attention from the research community. Schlimbach & Mitschang (2006) developed a model for estimating the tape placement time which accounts for shape complexity through a complexity factor. In their work they compare the theoretical times predicted by their model to place tapes on moulds with shapes of varying sizes and complexity to experimental results. They showed that the predicted layup times correspond very well to the actual layup times. As a result, their model will be used to predict representative times to add reinforcements.

The model developed by Schlimbach & Mitschang (2006) (equation 4.11) consists of three components. The first component accounts for the normal placement time for an area with no complexity; the second component accounts for shape complexity, while the last components accounts for delays in the placement procedure.

$$\Delta t_r = \sum_{i=1}^{N_L} \frac{A/(w \cdot v_0) + \sum_j (N_{ce} \cdot (\Delta t_{ce\zeta,tot_j} + 2 \cdot \Delta t_{a_j})) + n_s \cdot (t_{dead} + v_0/a)}{1 - r_{down}} \tag{4.11}$$

The various parameters in equation 4.11 are defined as follows: N_L is the number of layers to lay down; A is the surface area to lay down; w is the tape width; v_0 is the velocity at which tape placement occurs; N_{ce_j} is the complexity factor associated with the jth complexity element; $\Delta t_{ce\zeta,tot_j}$ is the process delay associated with the jth complexity component; Δt_{a_j} is the jth time delay caused by acceleration/deceleration due to the jth complexity component; n_s is the number of courses to lay down; t_{dead} is any other delays in the tape laying process such as the reorienting of the tape head during placement of adjacent courses; a is the tape head acceleration and, finally, r_{down} represents the fraction of machine downtime to the total available time.

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[5] Typical forming pressure of 2.0 MPa.

Since it has been decided that reinforcements will be added prior to the forming phase, the second component of equation 4.11 will naturally not be used. If, however, reinforcements are included after the forming phase, this component will need to be included. r_{down} will also not be considered in the current analysis.

The layup speed and acceleration of tape placement heads used in robotic tape placement are typically in the vicinity of 0.2 m/s and 15 m/s^2, respectively (Dell'Anno et al., 2012). Further, taking $t_{dead} \sim 1.5$ sec (typical delay), $w = 0.05$ m (typical tape width) and the area A as 0.053 m^2 (in the case study, the approximate length is 0.265 m and width is 0.2 m), a representative time to add reinforcements is found to be about 45 seconds.

4.5   Cell Configuration

The performance of a manufacturing system is significantly affected by the configuration of the various components, such as the machines, material handling systems and workers. Performance measures of a manufacturing system include its production rate, its ability to handle product variety and the lead time between product changeovers.

There are mainly three ways (figure 37) to arrange the components of a manufacturing system on the factory floor: by line, by function or in a cell (Bazargan-Lari, 1999).
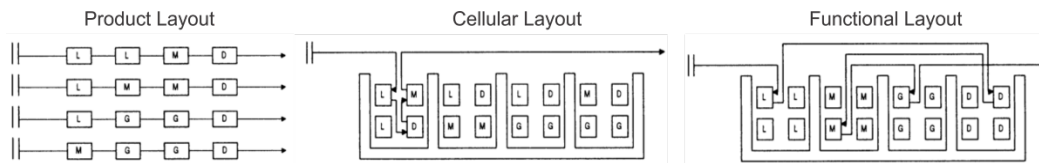
Figure 37: Types of manufacturing configurations (Shahtukh et al., 1999).

In the line (product) layout, all the components are arranged according to the sequence of processes that must be performed on a product. Advantages of this configuration are that it can handle high-volume production, product cost is low if product volumes are high and material handling is simple. However, this configuration cannot economically handle product variety and also cannot tolerate failure of machines or material handling equipment.

In the functional layout, similar or identical manufacturing components are grouped together which can perform the same processes. Unlike the line layout, this configuration is very fault-tolerant and can handle a large product variety. However, disadvantages include low machine utilisation rates, complex material handling, a large amount of work-in-progress and long manufacturing lead times (Bazargan-Lari, 1999).

Finally, in the cellular layout, different manufacturing components are clustered into cells which can perform a range of operations on a product. Although the use of cells can possibly result in higher investment costs, since machines may need to be duplicated across cells, extensive research has shown that cellular configurations hold

many advantages compared to the line and functional configurations and are therefore favoured in industry. For example, Askin & Estrada (1999) showed that, among others, cellular manufacturing reduces manufacturing cycle times, material handling and lead times between product changeovers, while it improves product quality and facilitates product variation well.

In the light of the advantages of cellular manufacturing presented above, the range of operations required to manufacture a seat pan will be clustered into cells as shown in figure 38. In the following sub-sections, two concepts for the thermoforming cell layout are developed. The building blocks of these concepts are all comprised of the sub-systems and material handling systems discussed previously.
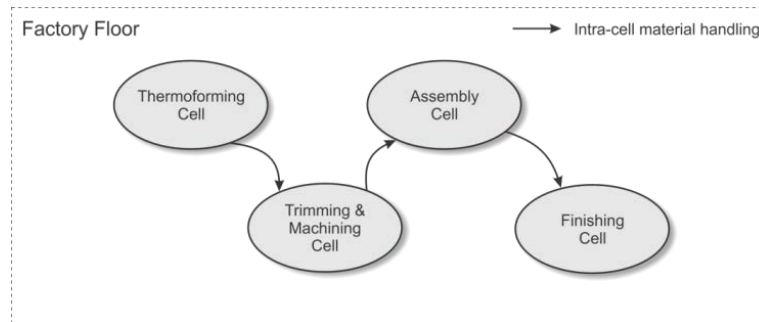
Figure 38: Cellular layout for the manufacturing of a seat pan.

4.5.1   Carousel Cell Concept

The first concept proposed here (figure 39) uses a conveyor arranged in a loop with removable pallets to transport material along the conveyor. All sub-systems are arranged around the perimeter of the conveyor which implements transverse conveyors (as indicated, for example, at the reinforcing station in figure 39) at each station. Using these transverse conveyors allows a pallet to be moved off the main line and therefore enables asynchronous processes at the various stations.

The blanks are first picked up from a buffer[6], using the articulated robot 'R1' with a vacuum gripper end effector, and placed in a fixture of a pallet on the conveyor. If reinforcements are required, the pallet is routed to the reinforcement station where the blank is then picked up by robot 'R3', also using a vacuum gripper end effector, and placed at the reinforcing station[7]. In this station, robot 'R2' will apply reinforcements using a tape placement head. When the reinforcement process has been completed, robot 'R3' will pick up and place the reinforced blank back into the original pallet. The pallet then returns to the main conveyor. When the pallet reaches a heating station, it is picked up and placed in a clamping frame of a heater by either robot 'R3' or 'R4', depending on the position of the pallet on the conveyor. When the blank has been heated to its forming temperature, the clamping frame is indexed

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[6] It should be noted that the a sheet cutting station was not included since this process is much faster compared to the other processes. Therefore, the blanks are cut and presented to the system in a buffer.

[7] It is assumed that the reinforcing procedure cannot be done directly on the pallet of the conveyor due to the high temperatures involved in this procedure.

into the forming station by a shuttling unit where the part is formed and cooled down under pressure. When the part has been formed, it is indexed back through the heater (heater is off at that time). The part is then unclamped and placed on the same pallet. The pallet then moves down the line and, if quality assurance needs to be performed, the pallet is routed to the quality assurance station. Here robot 'R5', which uses an appropriate instrument, checks for defects in the part. This operation can be performed while the part is still in the fixture of the pallet on the conveyor. Once the part has been inspected for defects, the pallet travels down to the end of the conveyor where robot 'R6' will pick up and place the part in an 'out buffer' using a vacuum end effector.
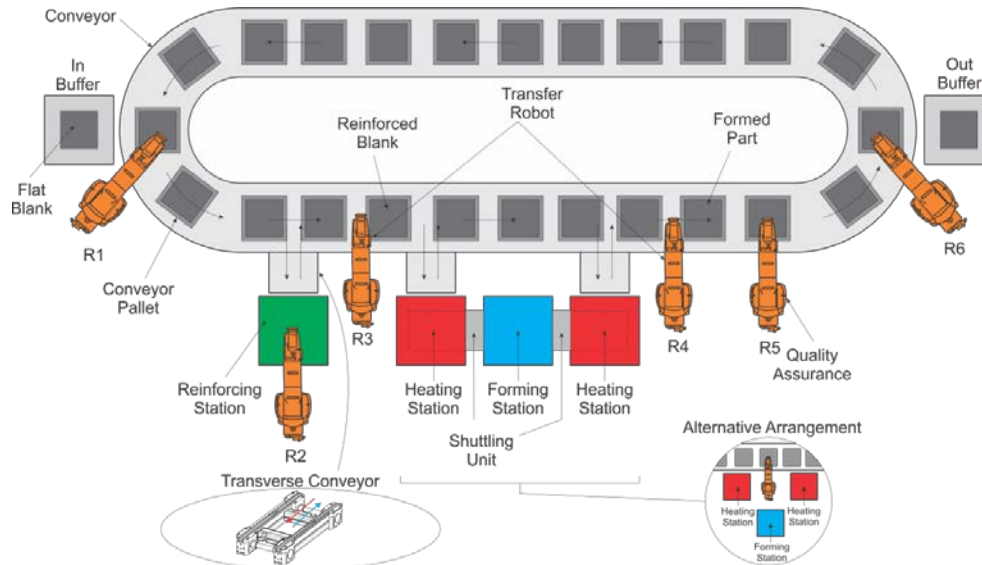
Figure 39: Carousel cell concept.

As indicated in figure 39, the heating and forming stations can be rearranged into an alternative configuration. Although this configuration will yield the same cycle times, it requires only one robot to transfer blanks between the heating stations. However, in this configuration, a dedicated and removable blank holder will be required which can be transported between a heating station and a forming station since it is not feasible to transport a heated blank by itself. The robot in this configuration will also require a more complex end effector since it will need to be able to pick up blanks from the conveyor and also be able to pick up and transport a blank holder between a heating and forming station.

In this looped configuration, assuming the two heaters[8] work in parallel and asynchronously and not considering the cycle time for part inspection, the cycle time to produce one part is equal to that of the forming time, since it is effectively the slowest process. For example, for an unreinforced seat pan, the cycle time is approximately equal to 60 sec/part. The cycle time of the system can be reduced by adding more stations on the opposite side of the conveyor.

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[8] From the cycle time analysis, performed in section 4.4, it was shown that the heating time for the seat pan was approximately twice as long as that of the forming time. Therefore two heaters were used in order to balance the line.

With regard to reconfigurability, an important advantage of this configuration is that it is scalable since the conveyor length need only be extended to add more machines. Scalability can possibly increase the fault-tolerance of the cell since redundancy can be incorporated and allows the production capacity to be increased or decreased according to customer demand.

However, there are disadvantages associated with this concept. Firstly, the utilization rates of the transportation robots 'R1', 'R3', 'R4' and 'R6' are low. Secondly, this concept requires a great deal of material handling equipment (4 robots, 1 conveyor and 1 shuttling unit) which may be very expensive. It is also noted that an interesting challenge in using this concept is that two types of pallets with two different fixtures will be required. One type of pallet needs to fixture a flat blank while another type of pallet needs to be able to handle a formed part. The fixturing of the formed part will be particularly challenging since each formed part has a unique shape around its perimeter after forming due to excess material.

4.5.2   Robot-Centred Cell Concept

The second concept proposed here (figure 40) uses an articulated six-degree-of-freedom industrial robot as the main transport mechanism with the sub-systems located around the workspace of the robot.

A central aspect of this concept is that the heating and forming stations are not linked by a shuttling unit. Since it is not feasible to pick up and transport a heated blank by directly contacting it, a detachable blank holder is required which can hold the sheet during heating and transportation and which can apply the required biaxial tension during forming. If a blank holder with pneumatic clamps is used, one challenge is to keep the clamp pressure during the heating, transportation and forming stages (since the pneumatic lines are also detached).

Since this concept uses a blank holder, as opposed to a pallet, to fixture a blank, this concept operates slightly differently from the concepts developed previously. The blanks are first picked from a buffer, using the articulated robot 'R1' with a vacuum end effector, and placed in a clamp-based blank holder at the loading/unloading station. Blank holders can be sourced from a 'blank holder magazine' or can be dedicated to a specific loading/unloading unit. Once the blank is placed in the blank holder, the blank is clamped. The whole blank holder is then picked up by robot 'R3', using an appropriate end effector, and placed at either the reinforcing station or heating station depending on the product requirements. If reinforcements are required, robot 'R2' will place reinforcements using a tape placement head. When the reinforcing process has been completed, robot 'R3' will pick up the blank holder and transport it to the heating station. When the sheet has been heated to its required forming temperature, robot 'R3' transports the blank holder to the forming station. When the product has been formed and cooled sufficiently, robot 'R3' subsequently transports the blank holder to the quality assurance station where robot 'R4' inspects the part for defects. Finally, after the part has been inspected, robot 'R3' transports the blank holder to the loading/unloading station where the part is unclamped and robot 'R1' places the finished part in a buffer.
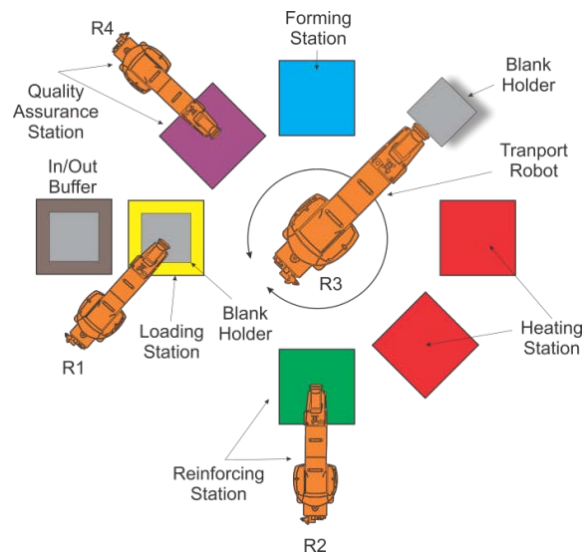
Figure 40: Robot-centred cell concept.

Although the scalability of this concept is limited to the work envelope of robot 'R3', there are many advantages which make this concept an attractive solution. One of the biggest advantages is that it requires much less material handling equipment. Comparing this concept to this carousel concept, only two robots are required for transport while four robots and a conveyor are required in the carousel concept. With an intelligent end effector for robot 'R3' for transporting a blank and a blank holder, it is noted that the number of transport robots in this concept can further be reduced to one robot. Therefore, this concept requires significantly less investment costs and possibly makes the control required for material handling much simpler. The utilization rate of the transport robot 'R3' is also significantly higher compared to the utilization rates of the transportation robots in the carousel concept. This is because robot 'R3' now performs all of the transportation tasks assigned to the transport robots in the carousel concept. Another advantage is that the sequence of processes for the product is easily changed since the path along which a robot moves can easily be reconfigured. Finally, in this concept, the part is fixtured only once which reduces the possibilities of faults and defects in the part as a result of multiple fixturing.

As a result of the limited scalability of this concept, the capacity scalability of the cell is limited and the cell has a low fault-tolerance since the scope to incorporate redundancy is also limited. Therefore, in order to increase the capacity and improve fault-tolerance, a whole new cell will be needed.

The carousel and robot-centred cell concepts both present viable routes for manufacturing the seat pan. However, it is deemed that the significantly lower investment cost of the robot-centred cell outweighs the scalability advantage of the carousel concept and, therefore, the robot-centred cell is selected and will be developed in the next chapter.

5.   Detailed Design and Synthesis

5.1   Introduction

Chapter 4 describes the conceptual design of an automated reconfigurable cell for the manufacture of a seat pan, including the development of the cell's architecture and configuration. It was shown in that chapter that the robot-centred cell is the more feasible configuration, compared to the carousel concept, for the manufacture of the seat pan.

This chapter describes the detailed design of the cell architecture in which the sub-systems of the robot-centred cell are developed in accordance with their functional and performance requirements. As a result of its central role in the robot-centred cell, the loading/unloading station (and its blank holder) is designed in detail while an off-the-shelf transport robot is specified. Other sub-systems, including the quick die change system, heating and forming stations, which are also available as off-the-shelf equipment, are not specified since their performance requirements are not clear at this stage. The remaining sub-systems, which include the reinforcing and quality assurance stations, are not designed or specified since these systems are not off-the-shelf equipment and still require significant research. The detailed design of the cell controller is given in chapter 6, while the cell configuration is implemented in chapter 7.

5.2   Blank Holder & Loading/Unloading Station

5.2.1   Functional and Performance Requirements

A central requirement of the robot-centred cell is a detachable clamp-based blank holder which can be transported between and placed at every station. The functional and performance requirements for the blank holder are listed below.

i.   Since the blank holder must be transportable throughout the cell, the pneumatic lines which supply air pressure to the clamps must be easily detachable/attachable. The air pressure must be held constant in order to maintain the clamping force during the transportation and processing stages when the air supply is detached.

ii.   In order to facilitate product variety, section 4.3.2 pointed out that the clamping forces supplied by the clamps are required to be adjustable and, therefore, the pneumatic air pressure must be adjustable. The research reviewed in section 4.3.2. showed that clamping pressures between 0.2 to 1.1 MPa is expected.

iii. A means of measuring the pneumatic air pressure supplied to the clamps is required for diagnosability.

iv.   In order to allow clamps to be quickly and easily added, removed or changed, the clamps must be removable and the clamp-frame mounting interface must be modular.

v.   The size of the blank holder frame must be quickly and easily adjustable to minimize the lead time for product changeovers and allow blanks of different sizes to be placed in the blank holder.

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5.2.2   Pneumatic Cylinder Actuation System

The pneumatic cylinder actuation system's diagram is shown in figure 41.
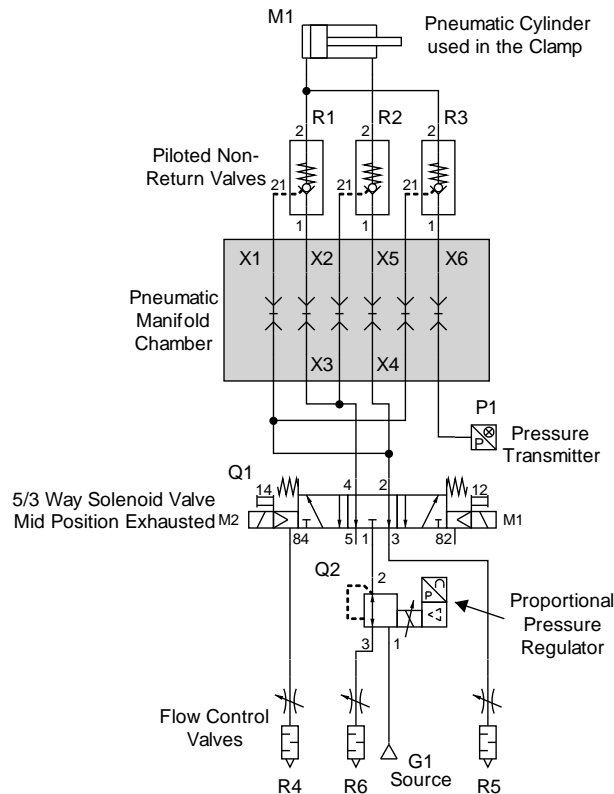
Figure 41: Pneumatic cylinder actuation system for the blank holder.

The input to the system is a constant pressure P_{max} (G1). This input pressure is regulated using a proportional pressure regulator, Q2, (MPPES-3-G1/8-6-010 model from FESTO). This regulator receives an analogue 0-10V control signal to allow the clamping pressure of the clamps to be quickly adjusted according to the material requirements.

To decouple the clamping cylinders (M1) from the pressure source, but keep the pressure constant when the source is decoupled, a pneumatic manifold (figure 42) and pilot-operated non-return valves (R1 and R2) are used, respectively (HGL-M5-B model from FESTO). The pneumatic manifold was custom designed and uses a double acting pneumatic cylinder, which is actuated by a 3/2 way electrically-switched solenoid valve, to open and close the manifold. The manifold uses couplings, which is mounted on a mating plate and uses O-rings to seal against the manifold chamber. An engineering drawing of the manifold is given in Appendix D.

As can be seen from figure 41, the non-return valves allow air flow in one direction only unless a pneumatic pilot signal is applied. Therefore, once the manifold has closed and pressure has been supplied to the pneumatic cylinders, the manifold can open and the pressure will be held within the cylinder barrel. Therefore, the force supplied by the clamp is held constant when the pressure source has been removed.
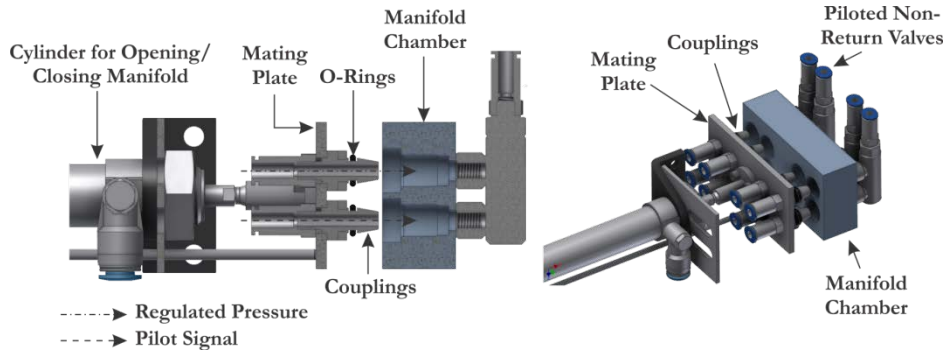
Figure 42: Pneumatic Manifold

To measure the pressure in the cylinders, a piezoresistive pressure sensor, P1, (SPTE-P10R-S4-V-2.5K model from FESTO) is used. This sensor receives a 0-6 bar pressure signal and proportionally outputs a 0-10 V analogue signal. It was also required that the pneumatic air line which connects the cylinder and the pressure sensor be detachable. Therefore, this line was also routed through the manifold and a pilot-operated non-return valve (R3).

Finally, a 5/3 way electrically actuated pneumatic solenoid valve (Q1) is used to switch the direction of airflow to open or close the clamps. This valve also uses flow control valves (R4 & R5) to control the speed of the air exhausted from the valve which directly controls the speed at which the clamps open or close.

A PLC was used to supply the analogue 0-10V control signal to the pressure regulator (Q2), measure the analogue 0-10V signal from the pressure sensor and provide the 24V digital output signals to actuate the 5/3 and 3/2 way valves. The Beckhoff BX9000 PLC was chosen since the TwinCAT software, which is used for the real-time communication with the PLC, provides a dynamic link library (DLL) which allows Java, which was used as the development environment for the holonic cell control system (detailed in chapter 6), to communicate to TwinCAT.

5.2.3 Blank Holder Frame and Clamps

To keep the blank holder mass as low as possible and allow the blank holder size to be quickly and easily adjusted, it was decided to use modular aluminium profiles and various connection elements (figure 43) from Bosch Rexroth.
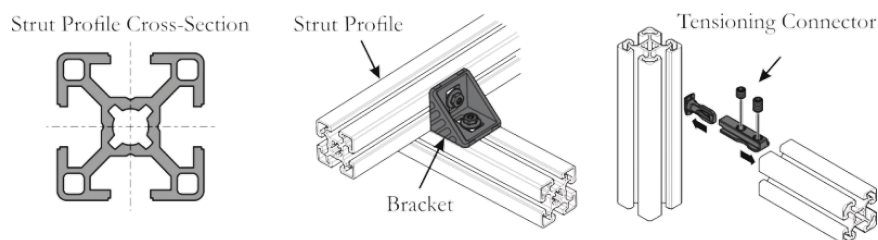
Figure 43: (a) Strut profile cross-section, (b) Brackets for connecting strut profiles (Adapted from Bosch Rexroth (2014)).

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The brackets and tensioning connectors allow the frame size to be quickly adjusted since they can be quickly and easily loosened and fastened with a standard Allen key. These connection elements have high load-bearing capacities which enable the frame to handle high static and dynamic loads.

To clamp a reinforced thermoplastic laminate sheet, the clamps shown in figure 44 were designed. The lower jaw of the clamp was designed with a step for accurately locating a sheet on the jaw, while the mounting plate was designed with a slot so that it can be accurately mounted on the modular profiles discussed above. The clamping force is supplied by the double acting cylinder, which was sized such that the pressure between the jaws could reach a maximum of approximately 0.6 MPa (ADN-50-50-I-P-A cylinder from FESTO). A larger engineering drawing of the clamp is given in Appendix D.
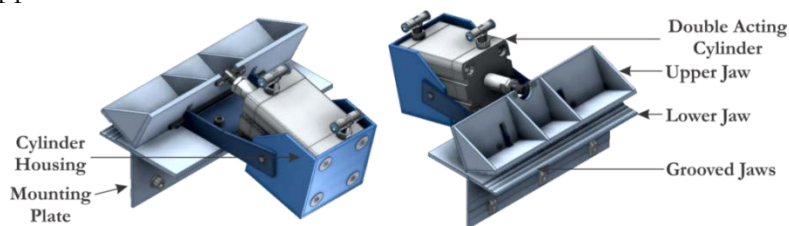
Figure 44: Clamps used for clamping a sheet.

5.2.4   Loading/Unloading Station

The pneumatic cylinder actuation system and blank holder with the clamps, discussed in the previous section, were assembled to form the loading/unloading station as shown in figure 45. It should be noted the blank holder was designed large enough to house two blanks to be able to form two seat pans at a time. In order to mount all the components, such as the manifold, PLC, pressure regulator, etc., and to accurately locate the blank holder, a frame made from 30 mm hot-rolled mild steel square tubing was designed. Stainless steel jigs were designed to locate the blank holder on the frame and are located at the top of each corner of the frame. An engineering drawing of the jig is given in Appendix D. To detect whether a blank holder is located on the frame and whether a blank is placed in the blank, two optical sensors were also incorporated into the loading/unloading station.

5.2.5   Proof-of-Concept

For the purpose of demonstrating the feasibility of the loading/unloading station and the blank holder (performed in chapter 7), the loading/unloading station was manufactured by the workshop at the Mechanical & Mechatronics Engineering Department of the University of Stellenbosch (figure 46). It should be noted that the proof-of-concept was built for forming only one blank and the pneumatic tubing used on the blank holder (not shown in the figure) was made of standard polyamide plastic tubing, which can tolerate a maximum temperature of 60°C. This was deemed acceptable for the proof-of-concept, but to withstand the high temperatures during the heating phase, the piping (and any other temperature sensitive components such as the internal seals of the cylinders) should be made from high-temperature resistant materials.
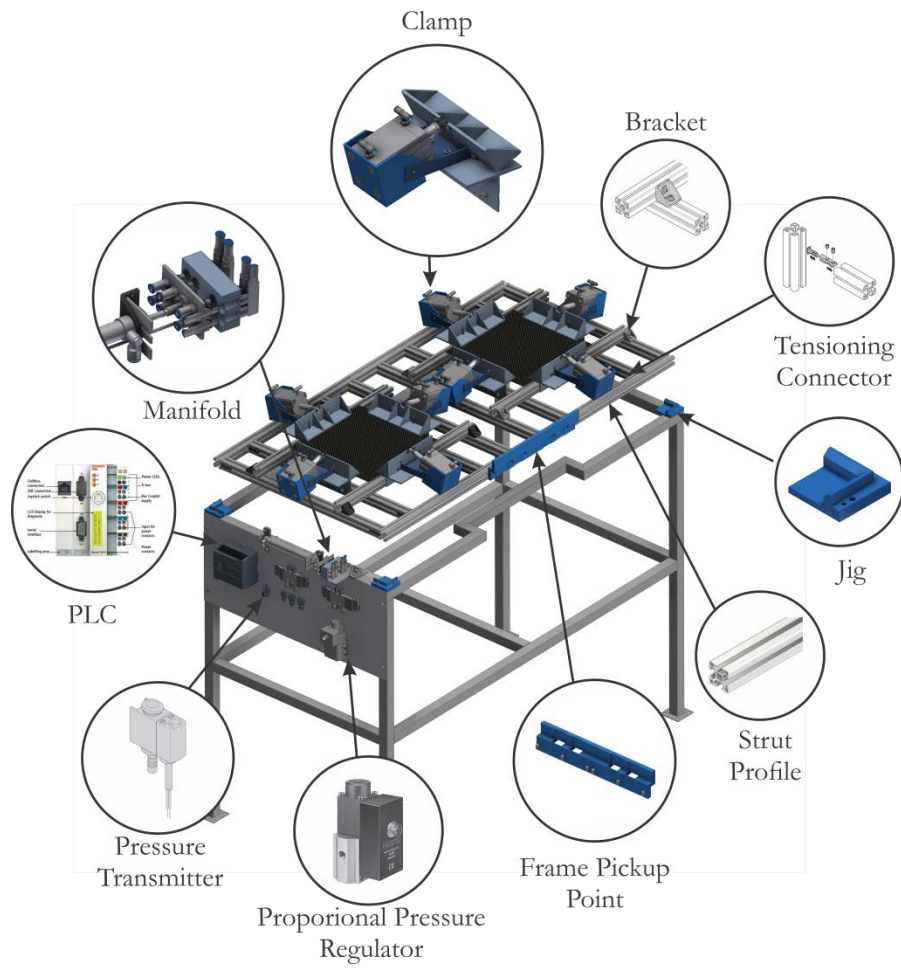
Figure 45: The loading/unloading station and blank holder showing all the sub-components.
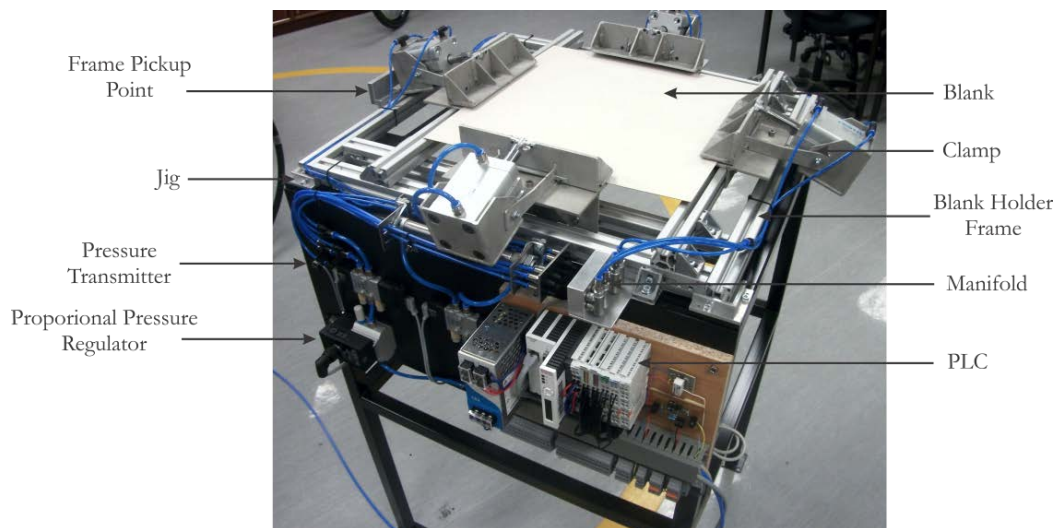
Figure 46: Loading/Unloading station proof-of-concept.

5.3   Transport System

5.3.1   Functional and Performance Requirements

The main transport system is an articulated six-degree-of-freedom industrial robot. The following functional and performance requirements were derived for the transport robot:

i.   The total mass of the blank holder in figure 45 was calculated to be approximately 21 kg. Therefore, the transport robot must have a payload larger than 21 kg.

ii.   The transport robot requires an end effector to pick up, transport and place the blank holder at the various stations in the cell.

iii.   The time to transport a heated blank from the heater to the press should be less than 5 seconds[9]. Therefore, the speed of the robot must be fast enough to satisfy this time requirement.

iv.   The work envelope of the robot must be as large as possible since the scalability of the robot-centred cell depends on this work envelope.

5.3.2   Selection of Transport Robot

There are a wide variety of manufacturers, such as ABB, Denso, Fanuc and KUKA, which supply articulated six-degree-of-freedom industrial robots for a variety of applications. KUKA is one of the largest industrial robot manufacturers and offers a broad range of highly modular robots with payloads ranging from 3kg to 1300 kg. A KUKA robot was selected for the transport robot since these robots use PC-based controllers, which allows third party applications to communicate to the controller through various fieldbus protocols, Ethernet or serial communication. KUKA also provides several simulation tools which enable the offline programming and simulation of robotic manufacturing cells. Finally, KUKA is well-supported in South Africa and has been extensively used by large companies such as Volkswagen South Africa.

KUKA cluster their range of industrial robots into four main categories according to their payloads as shown in table 7. From the table it can be seen the robots within the medium payload category satisfy the payload requirement to pick up the blank holder and, therefore, a robot from this category will be selected for the transport robot.

Table 7: Main categories of KUKA industrial robots and their payloads (KUKA, 2014).

Category	Payload
Low Payloads	5 kg – 16 kg
Medium Payloads	30 kg – 60 kg
High Payloads	90 kg – 300 kg
Heavy Duty	300 kg – 1300 kg

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[9] This time was obtained from a TenCate service engineer.

Figure 47 shows that the medium payload robots are further categorized into floor (or ceiling) mounted (orange/A-E) and shelf mounted (red/J-N) robots. The floor mounted robots are available in either standard (orange/A-E) or high accuracy formats (blue/F-I). The high accuracy robots provide a ± 0.01 mm improved repeatability over the ± 0.06 mm repeatability of the standard robots through the use of special gear units.
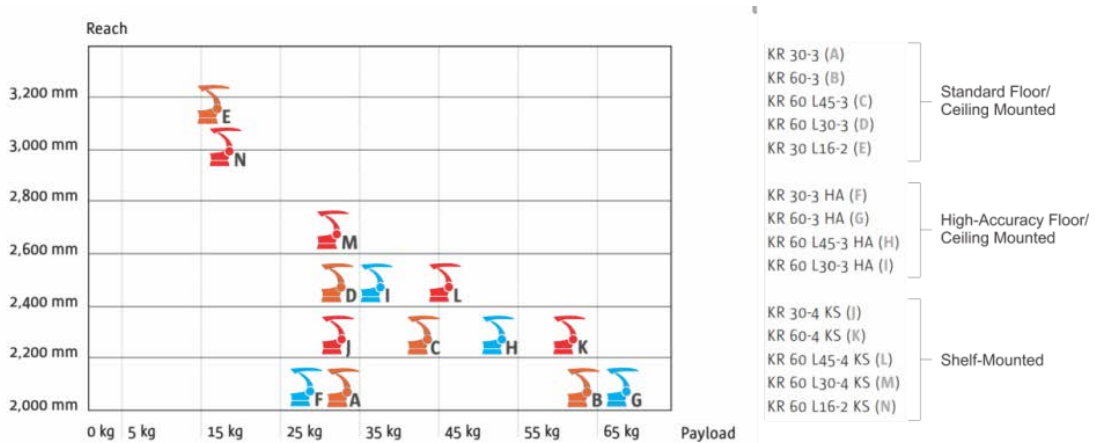
Figure 47: Range of Medium payload KUKA robots (Adapted from KUKA (2014)).

The KUKA KR 60 L30-3 and KR 60 L45-3 robot were selected as possible candidates for the transport robot because other robots had either excessive or insufficient payload capacity, a small work envelope (and therefore more limited scalability) or unnecessarily high accuracy. The following load analysis was performed to select between these robots.

The payload of a robot is a function of the distance to the centre of gravity (COG) of the object on its flange and decreases as the COG moves away from the flange. Therefore, the first test is to confirm whether the robots have sufficient payload to carry the blank holder on its flange. KUKA Load, a program specifically developed for static and dynamic load analysis of KUKA robots, was used to perform the payload analysis. Using the notation defined in figure 48 (a), the centre of gravity of the blank holder is at $L_x = -40$ mm, $L_y = 0$ mm and $L_z = 330$ mm. Figure 48 (b) shows the payload analysis results and indicates that both robots are within their operating ranges for a mass of 21kg. However, it is observed that the KR 60 L30-3 is very close to exceeding its operating range. This is confirmed by a static and dynamic analysis of each axis as shown in figure 49.

(a)   (b)
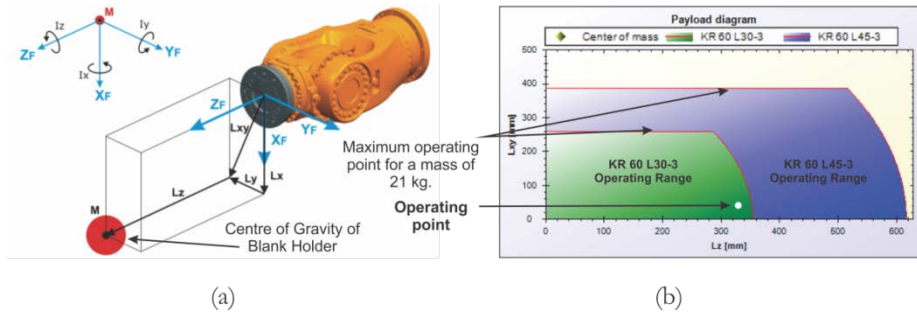
Figure 48: Payload analysis for the KR60 L30-3 and KR 60 L45-3 robots (Generated from KUKA Load (KUKA, 2014)).

The second test which needs to be performed is to check whether the robots can handle the dynamic loads imparted by the blank holder on each axis as a result of the mass moment of inertia of the blank holder. The test was again performed in KUKA Load and the result is shown in figure 49 (b). It is observed that both robots can comfortably cope with the dynamic loads imparted by the blank holder, although axis 4 of the KR 60 L30-3 is strained under dynamic loads.

(a)   (b)
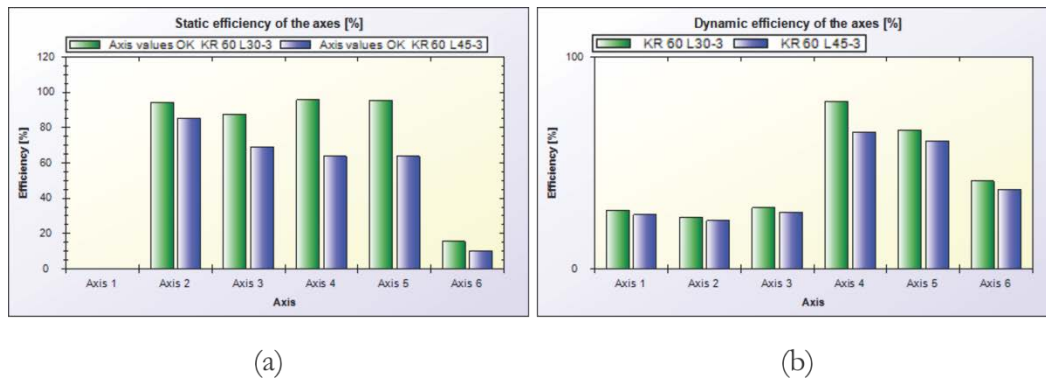
Figure 49: (a) Static and (b) dynamic efficiency of the KR60 L30-3 & KR 60 L45-3 robots (Generated using KUKA Load (KUKA, 2014)).

Although both robots are not statically or dynamically overloaded, it is seen that in both cases the KR 60 L30-3 is close to its operating range. Since it is possible that the blank holder may increase in weight as a result of adding clamps, the operating range of the KR 60 L30-3 may be exceeded. It is therefore deemed not a suitable option for the transport robot, and the KR 60 L45-3 was, therefore, selected.

5.3.3   Robot End Effector

To pick up, place and transport the blank holder, the end effector tool shown in figure 50 (a) was designed. It consists of a flange plate, which directly mounts on the flange of the robot, an end effector tool, which mounts onto the flange plate and a blank holder tool, which is mounted onto the profile of the blank holder. An engineering drawing of the flange plate, end effector tool and blank holder tool is given in Appendix D. The end-effector for the proof-of-concept is shown in figure 50 (b).

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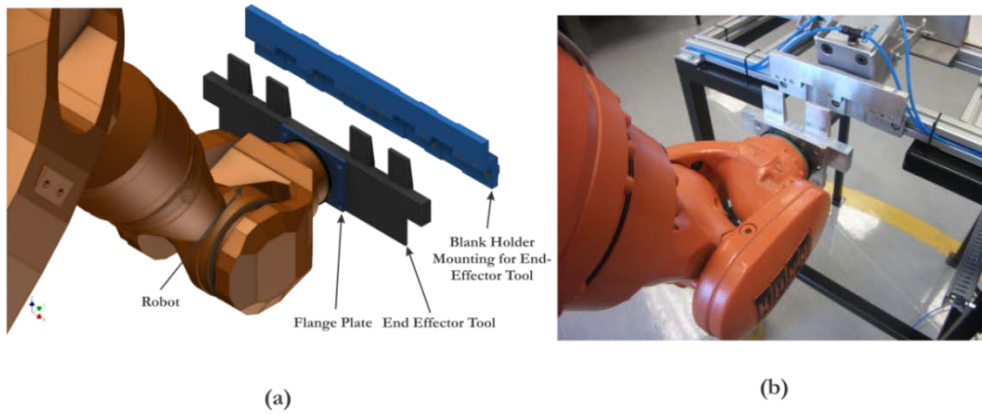
Figure 50: End effector tool for picking up, placing and transporting a blank holder.

6. Cell Control

6.1   Introduction

This chapter continues the development of the reconfigurable manufacturing cell with the design of the cell controller. The chapter first describes the cell controller architecture after which it details the implementation of the cell controller.

6.2   Cell Controller Architecture

Several manufacturing control architectures were reviewed in section 2.3. The holonic control approach supports the reconfigurability characteristics (section 2.2.2.1) well due to the modular and adaptive nature of holons. The former aspect enables scalability and integrability, while the latter aspect enables convertibility. Therefore, a holonic control approach is adopted here for the development of the cell controller.

Two holonic reference architectures were reviewed in section 2.3.2 namely ADACOR and PROSA. ADACOR was chosen over PROSA since Leitao *et al.* (2003) proposed a formal approach for specifying the structure and behaviour of a holonic manufacturing control system. In this proposal, the static structure of a HMS is specified, using the well-known UML (Unified Modelling Language) notation, while dynamic behavioural aspects are modelled using Petri nets. No such specification has been found for the PROSA reference architecture and as a result of the clearly defined guidelines given in the said proposal, ADACOR was chosen as the reference architecture for the development of the cell controller architecture.

As was pointed out in section 2.3.2.2, ADACOR proposes three types of holons, namely product, task and operational holons, to manage the core responsibilities of a decentralised manufacturing control system and a supervisor holon to introduce coordination and global optimisation. Therefore, the following holons, their responsibilities and inter-relationships for the robot-centred cell are identified and are shown in figure 51:

i.   Product holons: Each product type (e.g. a specific seat pan model) is represented by a product holon. A product holon receives (from a Human Machine Interface (HMI) or factory controller) the product and its production information.

For the seat pan made from RTL sheets, the product information includes the sheet dimensions, material density, material specific heat, the melt temperature of the sheet and the dimensions of reinforcements a product may require, etc. The production information includes the type and sequence of operations to be executed on the product by the resources in the robot-centred cell, as well as process parameters according to which the product must be manufactured (for example, the clamping pressure, the required heating time and the required forming time).
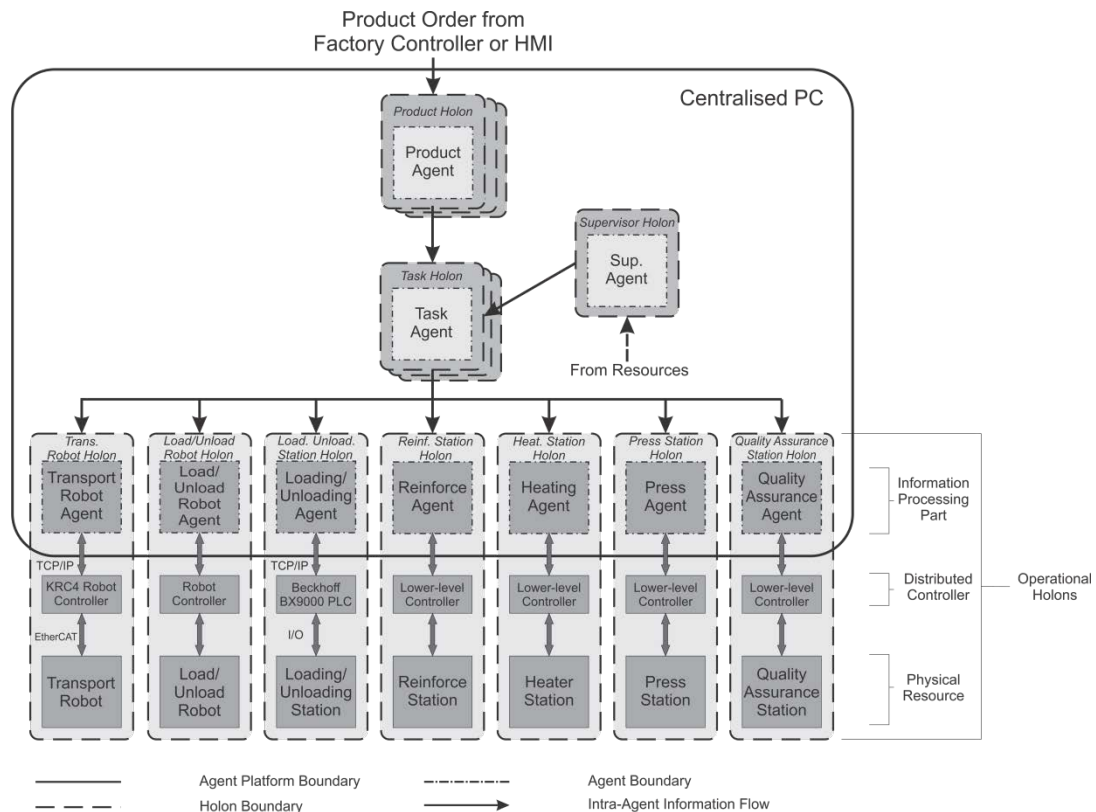
Figure 51: Thermoforming cell control system architecture.

ii. Task Holons: These holons control and monitor the manufacture of a product in the robot-centred cell. The task holon receives the production information from the product holon as input. The task holon uses this information to allocate resources which must perform the type of operations required on the product. Once the task holon has allocated a resource for a specific operation, it shares the process parameters with that resource for the correct manufacture of the part.

iii. Operational Holons: As shown in figure 51, an operational holon represents a physical manufacturing resource in the cell, its associated physical controller and its information processing part. Therefore, the operational holons within the robot-centred cell include a transport robot holon, a loading/unloading station holon, loading/unloading robot holon, reinforcing station holon, heating station holon, forming station holon and a quality assurance station holon. The operational holons receives, from the task holon, the process parameters to correctly manufacture the product.

iv. Supervisor Holon: In order to add opportunities for global optimisation and to coordinate groups of operational holons, a supervisor holon is added. The supervisor holon receives as input the capabilities of the various resources and advise the task holons during the resource allocation process which resources to allocate for a specific operation based on the specific resource capability.

As will be motivated in the following section, the information processing part of all holons were implemented using agents. All intra-agent communication is done through an agent communication language (ACL). Only the transport robot and loading/unloading stations were physically implemented. The physical controller of the transport robot is a KRC4[10] controller while the physical controller of the loading/unloading station is a Beckhoff BX9000 PLC. The TCP/IP protocol was used to communicate between the agents of the transport robot and the loading/unloading station and their respective controllers.

6.3   Cell Controller Implementation

It was pointed out in Section 2.3.4.1 that software agents provide the necessary tools to develop the information processing part of a holon (see figure 5). Therefore, a multi-agent system approach will be used to implement the information processing parts of the various holons in the robot-centred cell control system shown in figure 51.

Section 2.3.4.3 also pointed out that when adopting a multi-agent approach, it is convenient to develop the agents using an agent-oriented middleware which already provides the infrastructure for the development of agents. It was decided to use JADE (Bellifemine & Caire, 2000), which is implemented in Java, as the agent development environment (ADE) since it is the most widely used and actively supported ADE within the research community.

The following sub-sections first describe the development of the information processing parts of the holons using an agent based approach. Section 6.3.3 will then describe the functionality of the physical controllers of the resources which were physically implemented and the interfacing between the controllers and their agents.

6.3.1   Development of the Information Processing Parts using a Multi-Agent System approach

Before detailing the design of the agents developed for the cell controller, it is necessary to briefly describe several aspects related to the management and operation of the agents including the creation, location, registration, communication and coordination of the agents in the cell controller.

6.3.1.1   Agent Management

Figure 52 shows the agent management model used by JADE. It shows that an agent platform includes a directory facilitator (DF) and an agent management system (AMS). The agent platform (AP) is the physical infrastructure in which agents are hosted. For the robot-centred cell, the AP is a centralized PC as shown in figure 51. Therefore, all the agents reside within a single AP. In order to support the notion of distributed manufacturing and fault-tolerance, each agent could reside within a dedicated AP.

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[10] The KRC4 controller is used for the real-time control of all KUKA robots.
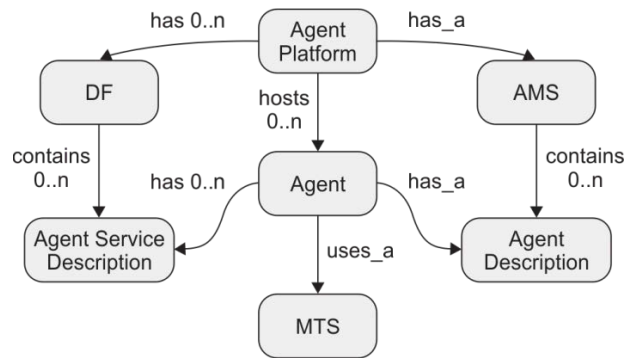
Figure 52: Agent management model (Bellifemine et al., 2007).

All agents within an AP has a skill(s) which it can offer to other agents. A skill within a multi-agent system is known as a service description. The DF maintains a description of all agent services and their identifiers (detailed below). Therefore, the DF acts as a centralized database from which an agent can search for a particular service offered by a particular agent. The agents descriptions within the robot-centred cell controller are summarized in Appendix E. For example, the heating station agent was given a service description of `Heat`. Therefore, if a task agent requires an operational agent which provides a heating service, it can find such an operational agent by searching the DF for a `Heat` service.

Every agent within an AP must have an agent description known as an Agent Identifier (AID). The most important elements of the AID are the agent name and its address. The agent management system (AMS) keeps a database and the current state (e.g. active, suspended, etc.) of all the agents present within an AP.

It was pointed out in section 2.3.4.2 that coordination of agents within a MAS requires agents to communicate information and knowledge. This Intra-agent communication is performed using ACL messages. The message transport service (MTS) is a service provided by the AP which manages the receiving and sending of ACL messages between agents.

6.3.1.2   Agent Coordination

The Contract-Net Protocol (CNP) (see figure 6) was used in the robot-centred cell controller for negotiation and delegating tasks among the agents in the cell. For example, if a task agent (acting as an initiator or coordinator) must delegate the task of heating an RTL sheet to one of several heaters (acting as responders or actors) that may be available in the cell, it uses the CNP to negotiate with all the available heater operational agents to heat the sheet and, eventually, to delegate the task to one of the heater operational agents.

JADE provides two classes to implement the CNP, called `ContractNetInitiator` and `ContractNetResponder`. These two classes provide the functionality for implementing the initiator and responder roles in the negotiation process, respectively. These classes consist of callback methods which generate and handle the messages shown in figure 6. These callback methods were redefined with the logic associated with the thermoforming domain.

Refining the example presented above, the task agent implements the `ContractNetInitiator` class while the heater operational agents implement the `ContractNetResponder` class. In order to request all available heaters to heat an RTL sheet, the task agent sends a call-for-proposal (CFP) to all available heater operational agents using the `prepareCfps(…)`callback method. This method was redefined with preconditions which must be met by a heater such as the size of the sheet that must be heated, etc. In order to receive the CFP from the task agent, the heater operational agents implement the `handleCfp(…)`callback method. If the preconditions can be met by the heater, this callback method returns a PROPOSE message to the task agent. Otherwise, if the preconditions cannot be met (for example, the heater cannot heat the sheet of the specified size), the method returns a REFUSE message. The task agent then uses the `handleAllResponses(…)` callback method to receive either the PROPOSE or REFUSE messages from all heater operational agents. The method then evaluates all proposals and, if one is acceptable, the method returns an ACCEPT_PROPOSAL to that particular operational agent. Otherwise it returns a REJECT_PROPOSAL message if the proposal was unacceptable. In order to receive the ACCEPT_PROPOSAL or REJECT_PROPOSAL messages, the heater operational agents implement the `handleAcceptProposal(…)`and `handleRejectProposal(…)` callback methods, respectively. If an ACCEPT_PROPOSAL message has been received by the `handleAcceptProposal(…)` method, the actual heating of the sheet is performed. The `handleAcceptProposal(…)`method, therefore, receives the process parameters sent from the product agent, such as the heating time, and heats the sheet accordingly. Once the sheet has been heated, the `handleAcceptProposal(…)` method returns an INFORM message to notify the task agent the operation has been completed. Otherwise, if the sheet failed to be heated for some reason (for example, due to heater failure), the method returns a FAILURE message to notify the task agent accordingly. The task agent implements the `handleInform(…)` and `handleFailure(…)` methods which receive the INFORM and FAILURE messages, respectively.

All the agents in the robot-centred cell controller implement the CNP classes for coordination. However, due to the nature of information flow shown in figure 51, the product agent only needs to implement the `ContractNetInitiator` class to initiate communication with a task agent while the operational agents only need to implement the `ContractNetResponder` class to respond to communication initiated by a task agent. Due to the bi-directional flow of information required from the task agent, it implements both the `ContractNetResponder` class, to respond to communication from the product agents, and the `ContractNetInitiator` class, to initiate communication with the operational agents.

6.3.2   Cell Controller Agents' Functionality

In this subsection, the complete functional behaviour of the product, task and operational agents are modelled using flow diagrams. The functional behaviour of the supervisor holon is not developed here since global optimisation and coordination of holons were not implemented in this thesis and will be the subject of future research.

6.3.2.1 Product Agent

In the event a new product order is placed (from, for example, a factory controller or HMI), a product agent (figure 54 (a)) is launched. The agent then reads in the product and production information contained in the order and derives the process parameters from the product information. A class called `CalcProcessParams`, which implement methods that calculate the process information using the models developed in section 4.4, was developed. The methods include `heatingTime(…)`, `coolingTime(…)` and `reinforcingTime(…)`. The product agent accesses these methods which receive as input the product information and returns the required process information.

To create a product order, a basic program (figure 53) was written in Java from which a user could specify various details for a new product order. Once the user specified the product order, the contents of the order was written to file in XML format. Once the product agent is launched, it reads in the XML based information from file. It should be noted that the user does not enter material specific information, such as the thermal conductivity or melting temperature an RTL sheet, since such information are properties of the material and is, therefore, sourced from an information database. For example, if the user enters Polyetherimide as the base material type for a seat pan, the programs sources all the material properties, such as the thermal conductivity and melt temperature, etc. from the information database. An extract from a product order is shown below figure 53.
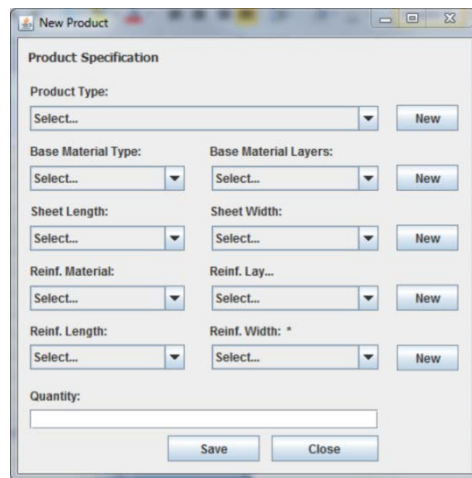
Figure 53: GUI for creating a product order.

```xml
<?xml version="1.0" encoding="UTF-8"?>
<ProductOrder>
  <Type>
      Seat_Pan
      <Material>CETEX_Polyetherimide_RTL_0.24mm</Material>
      <ClampPressure>0.3</ClampPressure>
      <Density>1910</Density>
      <SpecificHeat>1100</SpecificHeat>
      <MeltTemperature>310</MeltTemperature>
      <LayerThickness>0.024</LayerThickness>
```

```
        .
        .
    <Base_Material_Layers>4</Base_Material_Layers>
    <Sheet_Length>550</Sheet_Length>
    <Sheet_Width>550</Sheet_Width>
    <Reinforcement_type>CETEX_Polyetherimide_Unitape_0.24mm</Reinforce
    ment_type>
    <Reinforcement_layer>4</Reinforcement_layer>
    <Reinforcement_length>265</Reinforcement_length>
    <Reinforcement_width>200</Reinforcement_width>
    <Quantity>20</Quantity>
  </Type>
</ProductOrder>
```

When the product agent has successfully obtained the production and process information, it creates a task agent which is responsible for controlling and monitoring the manufacture of the product. The task agent receives the production and process information from the product agent and performs resource allocation, using the CNP, based on the production information. The product agent then waits for the task agent to complete. Once the task agent is complete, the product agent reports back that the product order has been completed after which the instance of the product agent is deleted.

6.3.2.2   Task Agent

When the product agent creates a task agent (figure 54 (b)), the task agent receives the production and process information from the product agent. The production information contains an array of $i = 1 \ldots n$-type operations that need to be performed on the product. The task agent starts with the first operation ($i = 1$) by querying the directory facilitator for a list of all available operational agents whose resource provides the first type of operation and requests the operation from all these operational agents by sending a CFP. If an operational agent is capable to perform the operation, it responds with a PROPOSE. If this proposal is acceptable, the task agent books the resource[11]. This booking of the resource is done to ensure that the resource does not accept another operation which could lead to a deadlock. Before the task agent requests that the operation be executed by sending an ACCEPT_PROPOSAL to the operational agent, it first books a transport service to transport the product to the booked resource. As soon as the transport service is available, the product is transported to the resource at which the operation must be performed. When the transport service has been completed, the task agent sends an ACCEPT_PROPOSAL message to the operational agent. This message contains the process parameters according to which the product must be manufactured. The relevant process parameters pertaining to the resource are parsed from the list of all process parameters received from the product agent. Once the operation has been

---

[11] The booking is done by the task agent by simply not returning an accept proposal message to the operational agent until the task agent actually requires the service to be performed. The resource is booked in this way since its resource's agent will wait for either an accept proposal or reject proposal message (or wait for a timeout) and will reject a CFP from any other task agents until it receives a response from the task agent it's engaged with.

performed, the operational agent sends an INFORM message to the task agent. The task agent continues the above process until all n operations have been performed and the product has been manufactured. When the task agent is complete, it notifies the product agent by sending an INFORM message after which the task agent is deleted.

6.3.2.3   Operational Agent

An operational agent (figure 54(c)) starts in a state where it waits for a request in the form of a CFP from a task agent to perform an operation. If a resource associated with an operational agent is busy, the operational agent will reject the request by sending a REFUSE message, otherwise if the resource is available and has the capability to perform the operation according to the preconditions set forth in the CFP, it will send a PROPOSE message to the task agent. If the task agent accepts the proposal, it sends an ACCEPT_PROPOSAL message. Within this acceptance message, the resource receives the required process parameters and will perform the operation according to the process parameters. Finally, once the resource has completed the operation, the operational agent notifies the task agent accordingly by sending an INFORM message and returns to a state where it is waiting for a request to perform an operation. If the resource failed to perform the operation, the operational agent will send a FAILURE message to the task agent.

6.3.3   Functionality and Interfacing of Physical Controllers

Since only the transport robot and loading/unloading stations were implemented, the following sub-sections describe only the functional behaviour of these subsystem's physical controllers and their interfacing with their respective resources' operational agents.

6.3.3.1   Loading/Unloading Station Control

As pointed out in section 6.2, the physical controller of the loading/unloading station is a Beckhoff BX9000 PLC, which uses TwinCAT for the real-time communication with the PLC. TwinCAT, acting as a server, allows client software to communicate to it through various open Microsoft standards, such as OPC, OCX and DLL. Therefore, this enables the client software to communicate with the PLC. The client software for the cell controller was written in Java and a DLL, called `AdsToJava.dll` (Beckhoff, 2013), provided by Beckhoff was used. This DLL provides various methods which can read and write to and from the analogue and digital inputs and outputs of the BX9000 PLC.

A class called `LUStationControl` was created with custom methods, which invoke the methods provided by the DLL, to provide the required functionality to unclamp a sheet or clamp a sheet with a specific pressure. These methods include `writeClampPressure(…)`, `closeClamps(…)` and `openClamps(…)`. These methods, therefore, wrote control signals, once the loading/unloading agent received an ACCEPT_PROPOSAL message from a task agent, to the proportional pressure regulator and solenoid valves to unclamp a sheet or clamp a sheet with a specific

pressure. A method, called `readClampPressure,` was used to read the feedback signal from the pressure sensor to measure the pressure in the pneumatic cylinders.
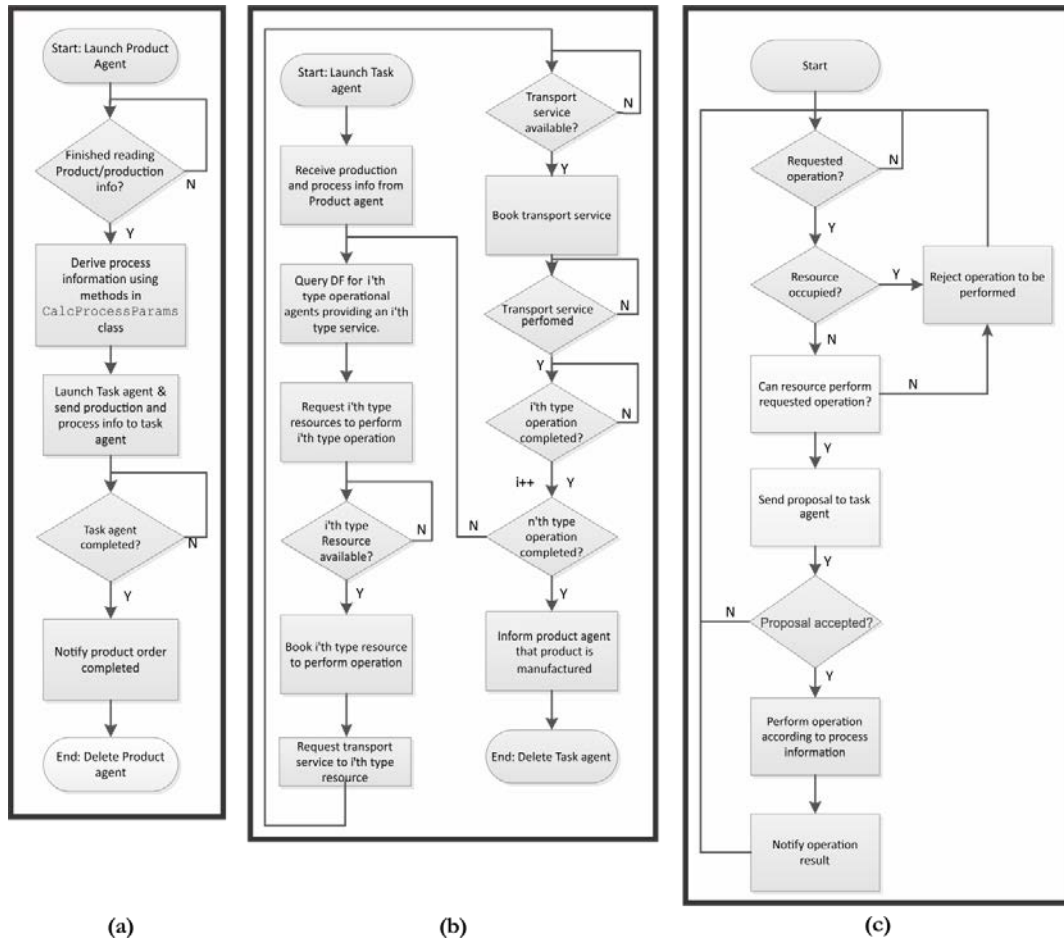
Figure 54: Flow diagrams for a (a) Generic product holon, (b) Generic task holon, (c) Generic operational holon.

6.3.3.2   Development of Transport Robot Control

To communicate between the transport robot agent and the KRC4 controller of the transport robot, a Java open-source communications interface, called JOpenShowVar (JOpenShowVar, 2014), was used. This interface enabled the agent to read and write variables of the KRC4 controller through the TCP/IP protocol.

As shown in Appendix E, the transport robot agent provides several services. These services were defined such that it covers all the possible transport routes within the robot-centred cell. The transport routes were pre-programmed in the KRC4 controller in its native language with each route programmed within a different function which could be invoked by a unique flag. Each flag was associated with a particular transport service of the robot agent. Therefore, if a task agent required a specific transport service from the transport robot agent, the transport robot agent *set* the flag corresponding to the required service in the KRC4 controller to TRUE using the communications interface described above. This invoked the necessary

function in the KRC4 controller and the transport service was performed. Once the transport service has been performed, the flag was return to a FALSE state. The same communications interface was used to communicate to the virtual controller of the simulated robot in the simulations which are detailed in the following chapter.

7. Evaluation

7.1   Introduction

This chapter serves, firstly, to evaluate the technical feasibility of the loading/unloading station and detachable blank holder developed for the robot-centred cell. With the aim to extract cycle times, derive resource utilization rates for different layouts of the robot-centred cell and to demonstrate the reconfigurability of the holonic cell controller, the chapter then describes various simulation experiments. In order to validate the simulation models, the loading/unloading station concept and the holonic cell control system, a physical experiment is also described.

7.2   Testing of Loading/Unloading Station

7.2.1   Testing of Blank Holder in a Heater and Press

This test was initially aimed at testing the detachable clamp-based blank holder, designed in section 5.2, in a heater and a press. The main aim was to observe whether the clamping pressure could be maintained, while the pressure source was removed, under heating and forming conditions and test whether the blank holder could be used to successfully form a seat pan. This test could, however, not be completed, as discussed below, and an alternative test, detailed in the next sub-section, was performed to test the blank holder.

This test was performed at AAT Composites and the test setup is shown in figure 55. As indicated in the figure, a radiant heater, which is used to heat an RTL sheet, is inline and next to a hydraulic press, which is used to form an RTL sheet into a seat pan. A shuttling system (similar to figure 27) is used to transport an RTL sheet between the heater and the press. The detachable blank holder was fixed to the shuttling system's frame such that it could be indexed between the heater and the press. In order to minimize the effect of the temperature on the pressure in the pneumatic cylinders and to protect the temperature sensitive parts within the cylinders, ceramic wool and foil was used to cover and protect the cylinders.

Figure 55: Test of blank holder at AAT Composites.

As mentioned, this test could not be completed since it was observed that, when the blank holder was positioned within the press, the upper die in the press, which is used to form the seat pan, would crash into the upper jaws of the clamps used in the blank holder. This was because the die used by AAT Composites for forming the seat pan was too large. AAT Composites did not have an alternative die available at the time that was both small and deep enough to bypass the upper jaws of the clamps.

In order to test the blank holder's ability to maintain the pressure inside the pneumatic cylinders, an alternative test was devised and is discussed in the following sub-section.

7.2.2   Testing the Reconfigurability of the Loading/Unloading Station

The focus of this test was to test the blank holder's ability to maintain a predefined clamping force, while the pressure source was removed, and to test whether the blank holder can be automatically reconfigured to vary the clamping force for RTL sheets with different material properties. Since the pressure measurements for this experiment were not conducted under heating and forming conditions, it is noted that the validity of the results regarding the ability of the blank holder to maintain the predefined clamping pressure is limited.

It was described in section 6.3.2 that a product agent receives a product order, which contains the product information, and derives the process information from the product information. Since the clamping forces for polyetherimide and polypropylene based composites were determined empirically and, according to the author's knowledge, no known model exists which predicts the clamping force for RTL sheets with different material properties, the required clamping force was stored and sourced from an information database. Therefore, when the user specifies either polyetherimide or polypropylene as the 'Base Material Type' using the GUI in figure 53, the product agent reads in the required clamping force from the information database corresponding to the specified base material. As described in section 6.3.2, the product agent then sends this information to a task agent. A task agent then searches for an operational agent in the DF which provides a clamping service which, as described previously, is provided by a loading/unloading station agent. Once the task agent contracts such an agent, it sends the required clamping force to the loading/unloading operational agent.

To conduct the test, polyetherimide and polypropylene was specified in the product specification in the GUI of figure 53 and respective clamping pressures of 0.3 and 0.5 MPa were selected based on the information in section 4.3.2. The pneumatic clamps can supply a maximum of 1178 N at 6 bar (the nominal supply pressure) at the clamping interface and the clamping area of the clamps is 0.002 m^2. Therefore, if the pressure regulator is given an analogue signal of 10 V, the maximum clamping pressure is supplied by the clamps which is P_{10V} = 1178/0.002 = 0.589 MPa. Therefore, in order to provide a clamping pressure of 0.3 MPa for polyetherimide and 0.5 MPa for polypropylene based RTL sheets, respectively, control signals of 5.09 V and 8.49 V were supplied to the regulator. The pressure sensor outputs a

signal of 0-10 V for a pressure range of 0-10 bar. Therefore, it should output approximately 3.06 V if a clamping pressure of 0.3 MPa is specified for polyetherimide and approximately 5.09 V if a clamping pressure of 0.5 MPa is specified for polypropylene.

Figure 56 shows the respective results when polyetherimide and polypropylene were specified as the base material type. It should be noted that the experiments were performed separately for each material and the results were superimposed in the graph of figure 56. The results were logged from the pressure sensor using a Beckhoff BX9000 PLC which could read in analogue 0-10 V signals. For both polyetherimide and polypropylene, the pneumatic cylinders were pressurized for a few seconds at the start by closing the manifold which routes the air pressure to the cylinders. The pressure source was then removed by disengaging the manifold for approximately 3 minutes to simulate the time a blank holder will be at the heating and forming stations. As described in section 5.2.2, the piloted non-return valves hold the pressure in the pneumatic cylinders when the pressure source is removed. After 3 minutes, the manifold was reengaged and the pressure in the cylinders was measured using the pressure sensor.
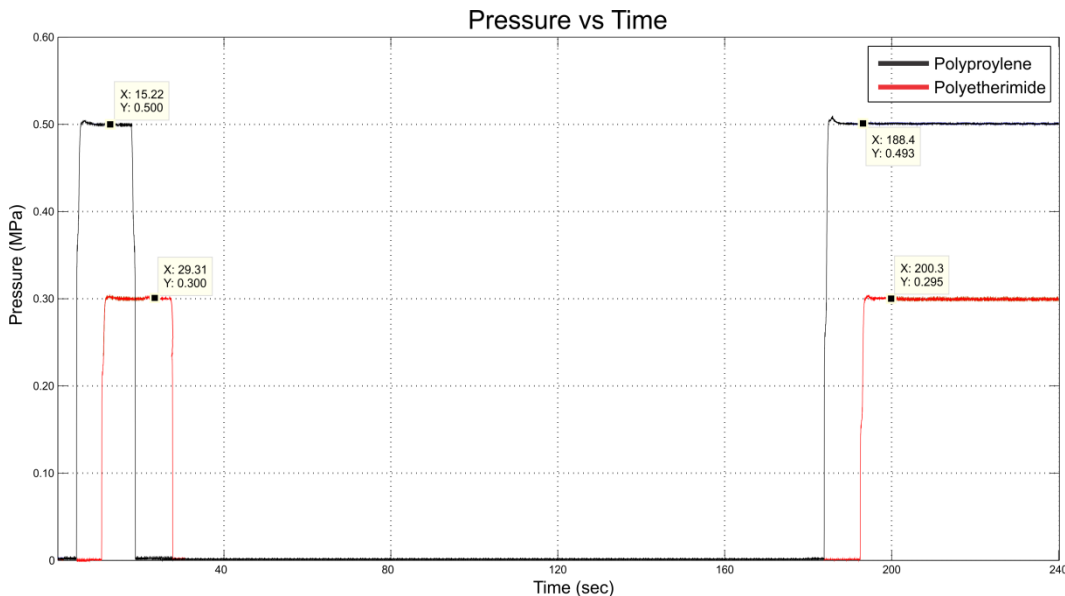
Figure 56: Result showing the pressure inside the cylinders for Polyetherimide and Polypropylene before and after the combined heating and forming time.

The graph of figure 56 shows two data points for each of polyetherimide and polypropylene. The first data point for polypropylene, which was sampled at 15.22 seconds, shows that a pressure of 0.500 MPa was measured. Similarly, the first data point for Polyetherimide, which was sampled at 29.31 seconds, shows that a pressure of 0.300 MPa was measured. Therefore, it is concluded that the blank holder was automatically reconfigured to vary the clamping force for the two types of material.

Finally, the second data points for both polypropylene and polyetherimide, which was sampled at 188.4 and 200.3 seconds, respectively, shows that pressures of 0.493 MPa and 0.295 MPa was measured, respectively. For polypropylene, this corresponds

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to a pressure drop of 1.38% while it corresponds to a pressure drop of 1.67% for polyetherimide. This pressure drop is deemed acceptable and it is noted that, if the blank holder was tested under heating and forming conditions, a pressure rise is expected as a result of the heating phase.

7.3   Reconfigurability and Performance Experiments

The following sub-sections describe three experiments which aim to derive cycle times and resource utilization rates for different layouts of the robot-centred cell and to demonstrate the reconfigurability of the holonic cell controller.

The robot-centred cell was developed with the use of KUKA Sim Pro, a 3D simulation program for the design and simulation of robot-based work cells. To make the building and design of a work cell easier, KUKA Sim Pro has a large library of parametric and kinematic CAD components. However, users can also design and integrate their own components. The program enables accurate cycle time prediction and can also perform collision detection within a work cell.

It should be noted that to simulate the sensors of the loading/unloading stations in all the simulations, which detects whether a blank holder and a blank is in position on the loading/unloading unit, a 'Get and Set' class called `GetSetLUStation` was used. This class contains *get* and *set* methods to get and set the availability of a loading/unloading station. The *get* methods were accessed by the loading/unloading station agents to determine its availability and, therefore, if it should send a proposal in response to a CFP from a task agent. The *set* methods were accessed via buttons on the main GUI written for the cell controller which was controlled manually to simulate a user putting a blank into the blank holder.

The speed of the transport robot is an important factor since the transport times add to the total cycle time for manufacturing the seat pan and the transport time between the heater and press needs to be as short as possible. A physical experiment, described in section 7.3.1, was performed in which a KUKA KR16-2 robot was used as the transport robot. It was determined from that experiment that a feasible speed to transport the blank holder was 40% relative to the maximum speed the robot is capable of. The KR16-2 robot is capable of moving its axis 1 (the main axis) at 156°/s. Therefore, the speed at which the main axis of this robot was moved was 62.4°/s. The KR60 L45-3 robot, which was used in the simulations, is capable of moving its main axis at 128°/s. Therefore, to achieve the same speed of 62.4°/s, the simulated robot was set to move at a speed of approximately 50% relative to its maximum speed. This speed was used in all of the simulations described in the following sub-sections. It should be noted that the transport speed can be significantly increased if an end effector is used which clamps the blank holder around its perimeter to increase its stability during transportation. The current end effector allows only the stated speed.

7.3.1 Experiment 1: Baseline

The first experiment, shown in figure 57, serves as a baseline against which the performance of the subsequent experiments will be evaluated and also to describe how resources are added and product changes are handled. The cell layout for this experiment includes only the necessary components for manufacturing an unreinforced seat pan, including one forming station, one heating station, two loading/unloading stations and a transport robot. Two loading/unloading stations (and their associated blank holders) were included because the detachable nature of the blank holder allows the heating and the forming phases to take place in parallel. Therefore, while one blank holder is in the forming station, another blank holder can be placed at the heating station. It should be noted that it was decided to replace the loading/unloading robot, which places blanks into the clamps of the blank holder, with a worker. This decision was taken since it would be more feasible, from a cost perspective, to use one worker to place blanks into the blank holders than use one robot at each of the loading/unloading stations.

For the cell in figure 57, a product order was placed, using the GUI of figure 53, specifying glass-fibre\polyetherimide as the base material type for the seat pan with no reinforcements. The number of layers was specified as 4, the size of the RTL sheets was specified as 550 × 550 mm and the quantity to manufacture was specified as 20.

Figure 57: Simulation of layout 1 with 1 forming station, 1 heating station and 2 loading/unloading stations.

The simulation was performed and the throughput rate and resource utilization rates were recorded. The results are given in figure 58. In order to compare the throughput rate of the cell with the conventional way of manufacturing an RTL sheet in a thermoforming process, figure 58 (a) also shows the expected throughput rate if a single shuttling system (described in Appendix B.3.3) with a clamp-based blank holder was used.

The results of figure 58 (a) show that the average throughput rate for a seat pan in the cell is $\frac{1602\,s - 210\,s}{20 - 2} = 77.3$ seconds per seat pan, while the average throughput rate for the single shuttling method is $1800/20 = 90$ seconds per seat pan. Therefore, the

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cell in figure 57 decreases the time to manufacture a seat pan by 14.1% relative to the single shuttling method. This represents an increase in output of 157 seat pans per 24 hour working day. This advantage can be increased if the transport speed in the cell is increased.
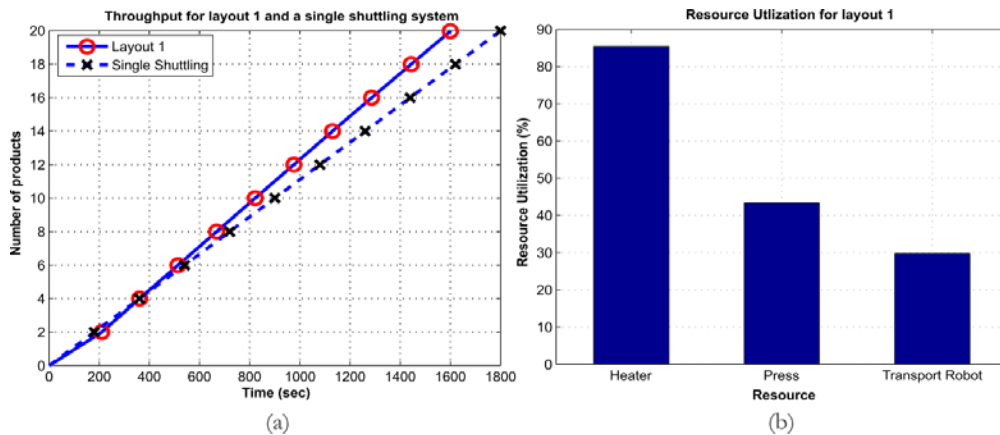
Figure 58: (a) Comparison of the throughput rate of the cell in figure 57 and the conventional single shuttling method. (b) Resource utilization rate for cell in figure 57.

Figure 58 (b) shows the utilization rates for the heater, press and transport robot of the cell in figure 57. The utilization rate of a resource was calculated by recording the total time the resource was actually used and dividing that by the total time the resource is available. Since the forming time is approximately twice that of the heating time for the current product specification, the press has to wait for the heating phase to complete. Therefore, as expected, the utilization rate of the press is very low. Since the press represents one of the most expensive components in the cell, this is very inefficient. In order to balance the cycle times between the heating and forming phases and increase the utilization rate of the press, another heater can be added as described in the next experiment.

In order to validate the loading/unloading station concept, the results obtained for the throughput of the simulated cell in figure 57 and the holonic cell controller, a physical implementation of the cell in figure 57 was performed. The experimental setup is shown in figure 59. Since only the loading/unloading station was built, mockups were used for the other stations.

The physical experiment showed that the blank holder could be picked up from and placed accurately into the jigs at the various stations and could be transported between the various stations without any problems. The blank holder could be repeatedly placed into the jigs of the loading/unloading stations and the manifold could be engaged accurately to pressurize the cylinders so that the clamps could be either opened or closed. Therefore, together with the results presented in section 7.2.2, the loading/unloading station is deemed a technically feasible concept.
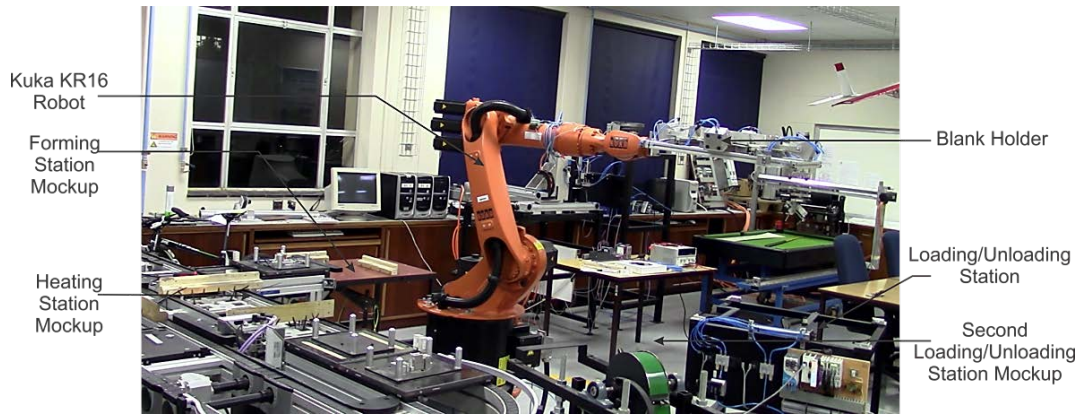
Figure 59: Physical implementation of the cell to validate the simulation, loading/unloading station concept and holonic control system.

Figure 60 (a) compares the throughput rate of the simulated and physical experiment. It is observed that the throughput rates are very similar, although the throughput rate for the physical experiment is slightly faster. This is attributed to the smaller transport distances which the KR 16-2 transport robot had to travel in the physical experiment[12].
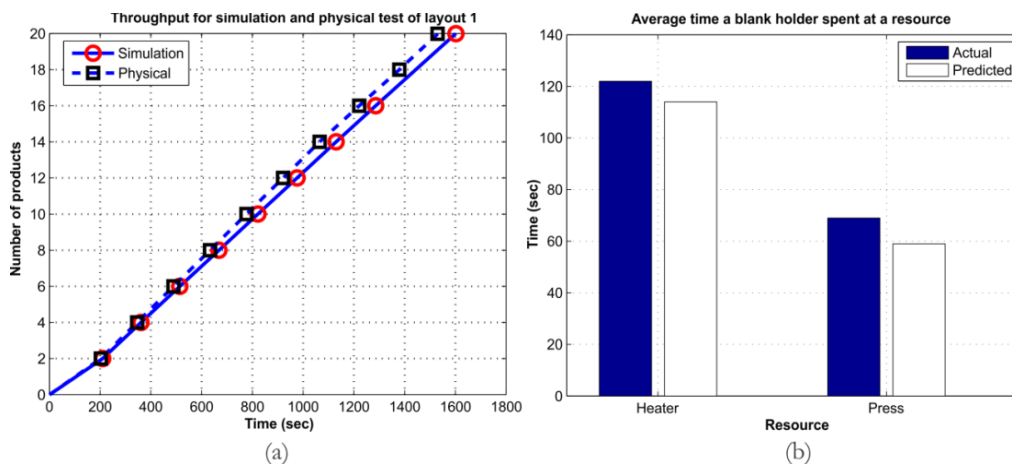
Figure 60: (a) Comparison of the throughput rate of the simulated and physical experiments (b) Average time a blank holder spent at a resource.

In order to confirm the correct operation of the holonic cell controller, a basic test was done to observe whether the heater and forming operational station agents received the correct process information (heating and forming time). In this test, the average time a blank holder spent at the heater and press was recorded over the production period and compared to the predicted process information. As shown in figure 60 (b) the predicted heating and forming time for the current product specification was 114 seconds and 59 seconds. The average time a blank holder actually spent at the heater and press stations was 122 seconds and 69 seconds, respectively, as shown in figure 60 (b). The slightly higher times the blank holder

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[12] Due to the smaller work envelope of the KUKA KR16-2 robot, the cell was made smaller.

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actually spent at the stations is attributed to the time it takes for the transport robot to reach the stations. Therefore, it is confirmed that the operational agents received the correct process information and, therefore, that the holonic cell controller operates correctly in this regard, although further development could improve the accuracy of the heater and press times.

7.3.2   Experiment 2: Addition of Hardware

This experiment aims to derive the cycle times and resource utilization rates if another heating station and loading/unloading station are added to the robot-centred cell and to demonstrate the reconfigurability of the cell controller with regard to adding resources.

A simulation was again performed in KUKA Sim Pro, in which a second heater (similar to the first heater) and a third loading/unloading unit (similar to the previous two) were added, and is shown in figure 61. In order to add a resource, its associated operational agent needs to be added to the cell controller. Adding operational agents to the cell controller is simplified by the modular and self-contained nature of the three types of agents used in the cell controller. For example, in the case of operational agents, they only require knowledge about the resource they manage and are shielded from logistical concerns (handled by task agents) and product related concerns (handled by product agents).

Figure 61: Simulation of layout 2 with 1 forming station, 2 heating stations and 3 loading/unloading stations.

If a unique resource, such as a heater with capabilities other than the existing heater, needs to be added, the agent class associated with the resource will first need to be created in which these capabilities are defined. However, if a similar resource is added and the agent class has already been defined, an instance of this predefined agent can be created and associated with the new resource. JADE provides a convenient tool (figure 62) for creating an instance of a predefined agent. Since a similar heater and loading/unloading unit will be added here, this tool is used to launch the agents associated for these stations.

By example, the class name of the existing agent of heater 1 is provided and a unique name called `HeatingAgent_2` is specified in figure 62. Therefore, when this agent is

launched, it is an exact duplicate of the operational agent which manages heater 1 in the robot-centred cell, although with a different name. However, the new heater is at a different position within the cell and, therefore, the coordinates specifying this position will need to be specified to the new agent. This information is sent to a task agent, once the heater agent has been contracted, which then sends the information to the transport robot agent in order to specify the location to which the blank holder needs to be transported so that the blanks can be heated. The JADE tool allows this information to be added in the 'arguments' slot of the GUI in figure 62. The arguments entered into this slot are passed to the constructor of the agent class once the agent is launched.

Figure 62: Tool to launch a new agent.

As described in section 6.3.1.1, each agent offers a service and as soon as the agent is created, it registers this service in the directory facilitator (DF). Since the second heater operational agent is exactly the same as the first heater operational agent, it will register a HEAT service in the DF as soon as it is created. Therefore, a task agent will be able to search for and contract the new heater as soon as the agent is created. The procedure described above was also followed to add a third loading/unloading agent to manage the third loading/unloading station.

For the layout in figure 61, the same product order was specified as in the first experiment and, therefore, the heating and forming times will be the same as in the first experiment. The simulation was performed and the throughput and resource utilization rates were recorded. The results are given in figure 63. In order to compare the throughput rate of the proposed layout with the throughput rate of the double shuttling method, figure 63 (a) also shows the expected throughput rate if a double shuttling system (described in Appendix B.3.3) with a clamp-based blank holder was used. Figure 63 (a) also includes the results obtained in the first experiment for comparison.

The results of figure 63 (a) shows that the average throughput rate for a seat pan using the cell in figure 61 is $\frac{976-219}{20-2} = 42.1$ seconds per seat pan while the average throughput rate for the double shuttling method is $\frac{1260-180}{20-2} = 60$ seconds per seat pan. Therefore, the cell layout in figure 61 decreases the time to manufacture a seat pan by 29.8% relative to the double shuttling method. This represents an increase in output of 612 seat pans per 24 hour working day. By comparison, the cell in figure 61 increases the output by 45.5% relative to the cell in figure 57. This represents an increase in output of 934 seat pans per 24 hour working day.

Figure 63 (b) shows the utilization rates for the two heaters, the press and transport robot in the cell of figure 61. It is observed, as expected, that the utilization rate of

the press in the cell of figure 61 has increased to approximately 69%, which is an increase of 26% compared to the utilization rate of the press in the cell of figure 57.

From a reconfigurability perspective, since the new resources that were added to the cell were successfully used in the simulation, it is concluded that the cell was successfully reconfigured.

(a)   (b)
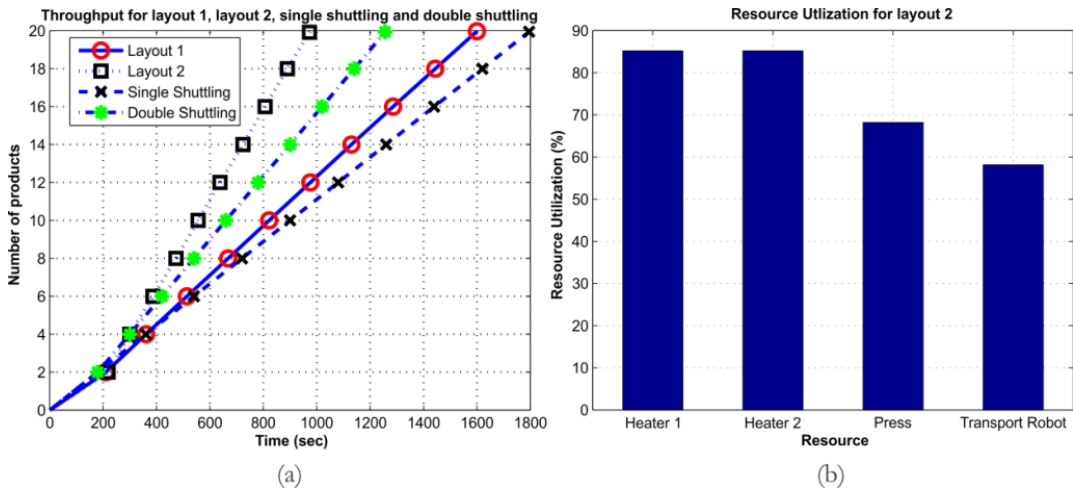
Figure 63: Comparison of the throughput rate of layout 1, layout 2, the conventional single shuttling and double shuttling method (b) Resource utilization rate for layout 2.

7.3.3   Experiment 3: Product Changeover

The focus of this experiment is to derive cycle times and resource utilization rates for the production of a reinforced seat pan using the cell proposed in figure 64. The experiment also aims to demonstrate the reconfigurability of the cell controller with regard to product changeovers. The cell includes all the stations used in the cell of figure 61, which was used for the manufacture of an unreinforced seat pan, but a reinforcing station and another loading/unloading station is added.

For the cell in figure 64, a product order was placed, again using the GUI of figure 53, specifying glass-fibre\polyetherimide as the base material type. The number of layers was specified as 4, the size of the RTL sheet was specified as 550 × 550 mm and the quantity was specified as 20. This is the same product specification for the cells in the previous experiments, except that reinforcements were also specified. The reinforcement material was specified as polyetherimide unidirectional tape and the number of reinforcing layers was specified as 4. The length and width of the reinforcements were specified as 265 mm and 200 mm, respectively.

Since two new resources, in the form of a reinforcing station and a loading/unloading station, were added, their respective agents also needed to be added to the cell controller. The reinforcing station agent class was programmed and this agent and the loading/unloading station agent were added in a similar way as described in section 7.3.2. The positions of both of the resources were specified in the argument slot of figure 62 when the agents were created.

The simulation for the cell in figure 64 was performed and the throughput and utilization rates were recorded. The results of the simulation are given in figure 65. The graph in figure 65 (a) compares the throughput rate for manufacturing a reinforced seat pan using the cell in figure 64 to the expected throughput rate of the single and double shuttling methods.
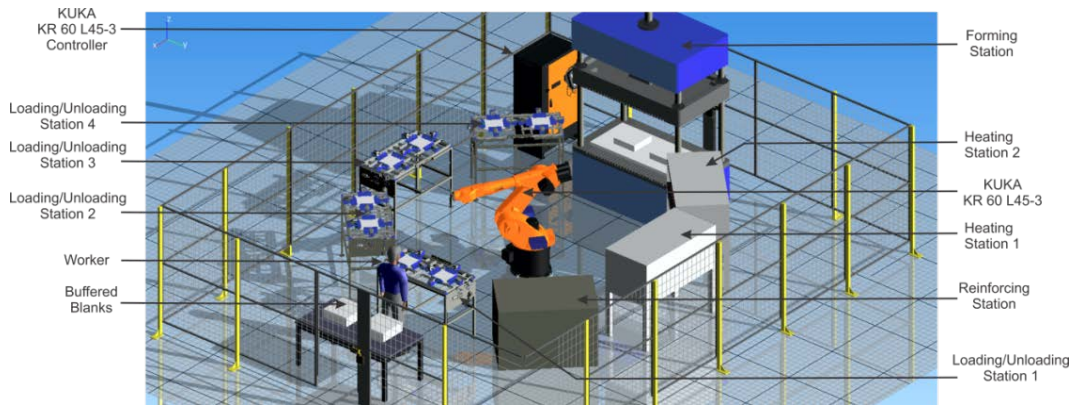
Figure 64: Simulation of layout 3 with 1 forming station, 2 heating stations, 1 reinforcing station and 4 loading/unloading stations.

The results of figure 65 (a) shows that the average throughput rate for a seat pan for the cell in figure 64 is $\frac{1755-399}{20-2} = 75.3$ seconds per seat pan while the average throughput rate for the single and double shuttling methods are 175 and 115 seconds per seat pan, respectively. Therefore, the cell in figure 64 decreases the time to manufacture a seat pan by 57.0% and 34.5% compared to the single and double shuttling methods, respectively. This represents an increase in output of 654 and 396 seat pans per 24 hour working day compared to the single and double shuttling methods, respectively.

Figure 65 (b) shows the utilization rates for the reinforcing station, two heating stations, press stations and the transport robot in the cell of figure 64. It is observed that the utilization rates of the various stations are very high which validates the feasibility of the cell from a cost perspective, if the cycle times are realistic.

In order to show that the cell controller was automatically reconfigured for the new product specification, a basic test was performed. In this test, the average time a blank holder spent at the various stations in the cell of figure 64 was recorded over the production period and is compared to the average time the blank holder spent at the various stations in the cell of figure 61, which received a different product order. For the product order received by the cell in figure 64, the predicted processing times for the reinforcing, heating and forming phases are 45, 117, 229 seconds, respectively, while the predicted processing times for the heating and forming phases in the cell of figure 61 are 0 (since no reinforcements were specified), 59 and 114 seconds, respectively. The recorded average processing times for the two cells are given in figure 66.
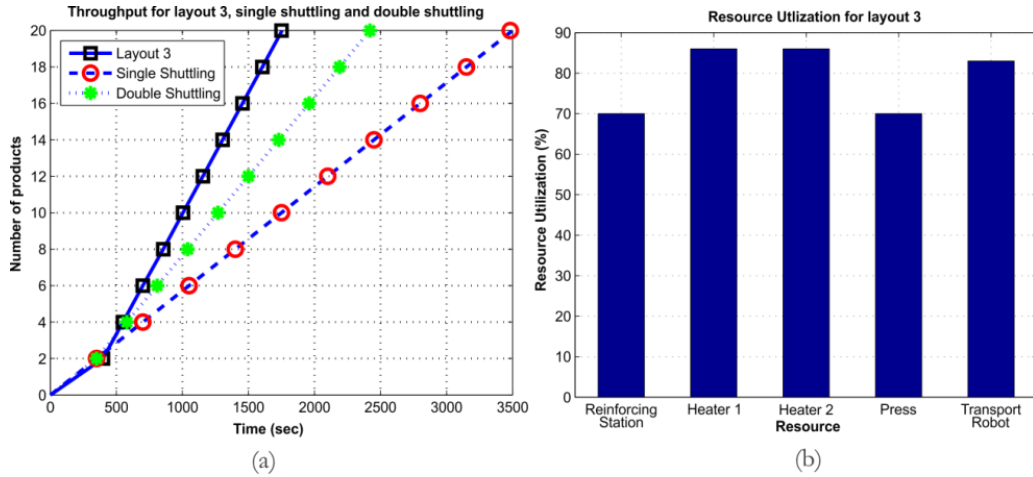
Figure 65: Comparison of the throughput rate of layout 3, the conventional single shuttling and double shuttling method (b) Resource utilization rate for layout 3.

The results shown in figure 66 confirm that the cell controller was automatically reconfigured for the new product specification in which reinforcements were specified for the seat pan. The results also show that the average time a blank holder actually spent at a resource is slightly higher than the predicted processing times. This is, again, attributed to the time it takes for the transport robot to reach the various
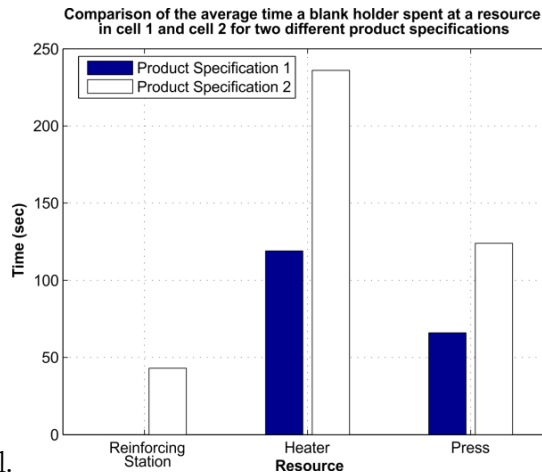
stations in the cell.

Figure 66: Average time a blank holder spent at a resource for two different product specifications in cell 1 and cell 2.

7.4   Discussion of Results

Section 2.2.2.1 pointed out that an ideal reconfigurable manufacturing system possesses six reconfigurable characteristics, namely modularity, integrability, customisation, convertibility, scalability and diagnosability, at a system, machine and control level. Using the results from the experiments conducted in sections 7.2 and 7.3, this section briefly discusses the reconfigurability characteristics the robot-centred cell exhibits.

The first test, detailed in section 7.2.2, showed that the clamping pressure of the blank holder could be successfully varied, using the pneumatic cylinder actuation system of the loading/unloading system, according to the product requirements. It is, therefore, concluded that the loading/unloading station and blank holder possesses the convertibility characteristic. Although not tested in this chapter, clamps can easily be added to, removed from or interchanged on the blank holder. This means that the blank holder possesses the modularity and integrability characteristics. Further, since the clamp positions can be adjusted in the blank holder, it can easily be adapted to clamp sheets of different sizes. Therefore, this aspect also shows that the blank holder possesses the convertibility characteristic.

The experiments in sections 7.3.2 and 7.3.3 demonstrated that, as a result of the self-contained modular nature of the product, task and operational agents used in the cell controller, adding resources to the robot-centred cell is simplified. The experiment in section 7.3.2 showed that a heater and a loading/unloading station were easily added, which shows that the cell controller possesses the modularity characteristic, while the experiment in section 7.3.3 demonstrated that a new resource, in the form of a reinforcing station, was easily added, which shows that the cell controller possesses the integrability characteristic. Finally, since the experiment of section 7.3.2 showed that the production capacity of the robot-centred cell was increased as a result of adding a second heater, the cell and cell controller possesses the scalability characteristic.

8.   Conclusions & Recommendations

This thesis documents the design of an automated reconfigurable manufacturing system for the production of thermoplastic fibre-reinforced composite parts, using as a case study a seat pan for commercial aircraft. The objective of the research was to assess the feasibility of such a system with regard to reconfigurability and throughput. There are several stages required for the manufacture of thermoplastic fibre-reinforced composite parts, but the current research focused only on the primary forming process while, secondary processes such as trimming, machining, assembly and finishing were not considered.

For the purpose of selecting the primary forming process of the seat pan, the design procedure firstly entailed investigating the range of manufacturing processes and intermediate thermoplastic material forms that are used commercially and in research for the automated manufacture of thermoplastic fibre-reinforced composite structural parts. The subsequent selection process showed that to use reinforced thermoplastic laminates in a thermoforming process is a feasible and attractive route.

With a manufacturing process selected, the conceptual design of the manufacturing cell's architecture and configuration was performed. The architecture design entailed investigating the state of the current research and industry developments regarding the constitutive sub-systems, which support product variety and quick product changeovers, of the thermoforming process.

Two promising configurations for the thermoforming process were investigated, namely the carousel and robot-centred cell concepts, which comprise the various sub-systems investigated in the architecture design phase. The carousel concept promises good scalability, but the utilization rates of the various transport systems are low. The robot centred cell offers limited scalability, but requires less initial investment capital as a result of its fewer transportation systems. The robot-centred cell was selected for development in this thesis because of the lower initial investment capital required. However, further consideration of the carousel concept, considering its possibly higher throughput rate and better scalability is recommended.

A central requirement of the robot-centred cell is a clamp-based blank holder which can be transported between the sub-systems, while the pressure source of the clamping cylinders is disconnected. A detailed design of such a blank holder, in which the pressure is held within the pneumatic cylinders' barrels throughout the manufacturing cycle, is presented.

Two critical aspects, which greatly influences the feasibility of the robot-centred cell, is the speed and 'response time' of the transport robot. The first aspect is important since the time in which a heated blank is transported to the forming station should be as short as possible and a slow transportation speed, in general, may also negatively affect the throughput rate of the cell. The second aspect, the response time of the robot, which is determined by both the speed of the robot and intelligence of the cell controller, is a measure of the time the robot takes to respond to a request to transport a blank holder from the heating station to the forming

station. It was shown that the blank could spend up to 10 seconds in the heater after it has been heated to its forming temperature. This is due to the slow transport speed and response time of the robot. The slow response time is, however, a result of the relatively simple control algorithm of the cell controller. To reduce the response time of the robot, some means of prioritizing the demands on the transport robot should be implemented. This could be implemented by incorporating a supervisory element into the agent based cell controller developed for the robot centred cell.

The reconfigurability and performance of the manufacturing system was evaluated through four experiments. The first experiment entailed testing whether the clamping pressure of the blank holder developed in this thesis could maintain a predefined and material specific clamping force and whether this clamping force could be varied according the different material requirements. The experiment showed that both these aspects could be achieved. The subsequent experiments evaluated the throughput rate and utilization rates of the resources for different layouts of the robot-centred cell and the ability of the system to be reconfigured to handle to new hardware and product changes. The performance experiments provided the grounds for assessing the feasibility of the system. From the results, it was concluded that the system exhibits a significant advantage in terms of throughput compared to the conventional techniques in which shuttling systems are used, while the system could be successfully reconfigured to handle hardware additions and product changes. It was concluded from these results that the manufacturing system exhibits various reconfigurability characteristics including modularity, convertibility, integrability and scalability.

An important aspect in manufacturing systems is the time and effort required to reconfigure the system for product changeovers, particularly on a control level. The current system was not evaluated in this regard, since to evaluate the feasibility of the system with regard to changeover times and effort requires a reference point. Since only agent technology was used for the control of the manufacturing system, a comparative analysis could not be performed to assess the feasibility of the agent-based cell control system. However, it is generally accepted that agent-based control systems significantly decrease the reconfiguration time of a control system compared to conventional, centralized, control systems.

This thesis aimed to show the feasibility of an automated, reconfigurable manufacturing system, which is used for manufacturing a thermoplastic fibre-reinforced composite seat pan, with regards to its reconfigurability and throughput. Other aspects that are very important, which influences the feasibility of such a system as a whole, include an assessment of the cost of the system and achievable quality of the parts manufactured by the system. Only after considering these factors can such a system be deemed viable.

Appendix A : Fibre-Reinforced Composites

A.1   Introduction

Fibre-reinforced composites are heterogeneous materials consisting of fibres of high strength and modulus embedded in a matrix. This combination yields a material boasting a collection of properties that cannot be achieved with either of the constituents alone. The fibres serve as the principle load-carrying members and therefore define the strength and stiffness properties of the composite (Army Armament Research Development and Engineering Center, 1991). The surrounding matrix distributes applied loads throughout the composite, holds the fibres in position and protects the fibres from environmental factors such as excessive temperatures, humidity and corrosive chemicals. The matrix, therefore, define the shear and environmental resistance properties of the composite (Army Armament Research Development and Engineering Center, 1991). The most widely used reinforcing fibres include carbon, glass, Kevlar 49, boron, silicon carbide and aluminium oxide (Mallick, 2007), while the most common matrix materials are polymers, metals and ceramics.

This section will focus on polymeric matrices and will start with a comparison between thermoset and thermoplastic composites and then motivate why the latter are gaining preference in industries such as the aviation and automotive industries.

A.2   Thermoset versus Thermoplastic Fibre-Reinforced Composites

Thermoset and thermoplastic FRCs are similar in the sense that they use the same fibre reinforcements. However, the difference between these composites lies in the matrix material which holds these fibres together. Traditionally, thermoset polymers have been preferred in industry as the matrix material for FRC parts. Mallick (2007) points out that one of the main reasons for this trend in industry was due to the ease of incorporating continuous fibres into the thermoset matrices due to the much lower viscosity of thermoset matrices. However, with the development of thermoplastic polymers that hold distinct advantages over thermoset polymers, more attention has recently been given to thermoplastics as a polymer matrix for FRCs. The following paragraphs consider the advantages and disadvantages of thermoset and thermoplastic FRCs.

Apart from the ease with which fibres are incorporated into thermoset matrices, Mallick (2007) reported the following advantages of thermoset polymers:

i.   High thermal stability. This implies good dimensional stability at high temperatures.
ii. High chemical resistance properties.
iii. Less creep and stress relaxation when compared to thermoplastics.

The disadvantages of thermoset polymers are (Mallick, 2007):

i.   Limited storage life at room temperature implying that these polymers require special storage conditions.
ii. Requires long fabrication time in the mould. This is due to a curing reaction that needs to take place to transform the liquid polymer to a solid polymer.
iii. Low strain-to-failure implying low impact strength and fracture toughness.

Yeung & Kamineni (2007) and Mallick (2007) reported the following advantages of thermoplastics:

i.   Higher tensile moduli compared to thermosets implying higher compressive strengths when compared to thermosets.
ii. Unlimited storage life at room temperature which means no special storage conditions are required.
iii. Shorter manufacturing cycles since no curing reaction needs to take place during forming as in thermosetting polymers.
iv. Joining and repairing are easily achieved by welding methods.
v.   Higher strain-to-failure compared to thermosets which implies a higher impact strength and fracture toughness compared to thermoset composites.

The disadvantages of thermoplastics are:

i.   Requires higher forming temperatures and pressures due to the higher melt viscosity of thermoplastic polymers (Hou et al., 1998).
ii. Some thermoplastic polymers present poor chemical resistance properties.
iii. The cost of most thermoplastic resins are higher compared to thermoset resins.

A.3   Matrix and Fibre Selection

Mallick (2007) states that the primary criteria used in the selection of a matrix for composite parts are the tensile modulus, tensile strength and fracture toughness. In the comparison above, it is observed that thermoplastic polymers have superior qualities in all three of these aspects. Díaz & Rubio (2003) also mentions that the higher cost of thermoplastic polymers can be justified since thermoplastic composites have shorter manufacturing cycle times and therefore increases the throughput rate of composite parts potentially leading to higher profits.

However, limiting the selection criteria to performance properties as indicated above is potentially sub-optimal. Other factors such as quality requirements and the choice of application also need to be included to fully justify the selection of a matrix for composite parts. As mentioned in the previous section, thermoplastic matrices do not need special storage conditions to prevent them from polymerising which may lead to inconsistent quality and performance properties. Therefore, repeatable quality requirements can more easily be satisfied by using thermoplastic matrices. Also indicated in the previous section, it is more difficult to achieve fibre wet-out (incorporation of fibres into the matrix) in thermoplastic composites and therefore it is more difficult to achieve a uniform fibre distribution in a thermoplastic matrix. This leads to a low fibre volume fraction which limits the strength of the composite

part (Mokhtar, 1995). This, therefore, limits the application of thermoplastic composites to lightly loaded structures.

In the light of the advantages presented above, it is clear why thermoplastic polymers are gaining preference in industry. However, the selection of a polymer matrix should be based on a comprehensive analysis of the particular application, taking into account various factors including performance, cost and quality requirements.

Appendix B : Thermoplastic Fibre-Reinforced Composite Material Forms and Manufacturing Processes

B.1   Introduction

In order to select the most suitable material form for the manufacture of a seat pan (which is the target product in this research), the intermediate thermoplastic FRC material forms commercially available, namely unidirectional prepreg tapes, semi-preg fabrics, reinforced thermoplastic laminates and moulding compounds, are reviewed. The section also reviews the current state of the automated manufacture of thermoplastic FRC's, particularly reviewing the technologies and control approaches that have been used.

B.2   Thermoplastic Fibre-Reinforced Composite Material Forms

B.2.1   Tapes

Thermoplastic unidirectional pre-preg tapes are supplied in various widths ranging from a minimum of 3.125 mm to a maximum of 300 mm (Groppe, 2003) and are made by impregnating continuous fibre tows with a thermoplastic matrix. An example of a thermoplastic unidirectional pre-preg tape is shown in figure 67.

This pre-preg form offers several advantages compared to other intermediate material forms. The full impregnation means components can be manufactured at low pressures and in shorter times. The material also offers the best opportunity to maximize the mechanical properties of a part, such as the strength to weight ratio, since the unidirectional nature of the tapes allow the fibre architecture of a part to be locally tailored to predicted loading conditions. Finally, since these tapes can be cut to any required length, local plies (doublers) can easily be added to match the size and shape of any reinforcements a part may require.

Unidirectional pre-preg tapes, however, are not as easily drapeable when compared to other intermediate thermoplastic material forms such as semi-preg fabrics. Since these tapes are fully impregnated and have a high volume fraction (~60 vf%) of fibre reinforcement, the ability to form this material into complex parts is limited and is normally constrained to single-curvature parts. This poor drapability causes a very demanding manual layup process which may increase cycle times to fabricate parts and an associate reduction in production volume.
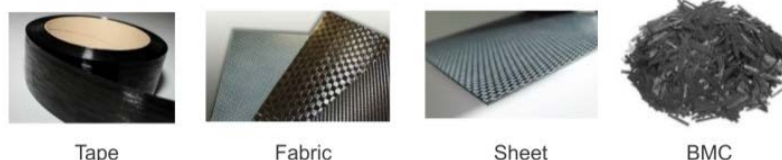
Figure 67: Thermoplastic intermediate material forms. (Royal TenCate, 2013).

B.2.2   Fabrics

Thermoplastic based fabrics are available in semi-preg form which differs from thermoset pre-preg fabrics in that the polymer matrix either resides on the surface of the fabric or polymer strands are woven between fibre tows. Two forms of semi-preg fabrics are commercially available: commingled and powder impregnated fabrics. Commingled fabrics are produced by weaving tow bundles, which are a mixture of continuous fibres and matrix strands, into a fabric. Powder impregnated fabrics are produced by impregnating fibre tow bundles with fine thermoplastic particles. The tow bundles are then subsequently weaved into a fabric. Semi-preg fabrics are supplied on spools in various widths of up to 1800 mm and ply thickness between 0.01 to 0.8 mm. An example of a semi-preg fabric is shown in figure 67.

As a consequence of the unconsolidated nature and low fibre volume fraction (~35-50 vf%) of semi-preg fabrics, these materials exhibit better drape properties compared to pre-preg tapes and are, therefore, able to be formed into more complex parts with double curvatures. As a consequence of this better handleability, layup time and layup effort are decreased when compared to pre-preg tapes which translates into decreased cycle times to fabricate parts which in turn translates to higher production volumes and lower labour costs.

Although semi-preg fabrics exhibit excellent drape properties, this material form has largely been constrained to hand layup since the manipulations needed to shape a piece of fabric to conform to a mould surface have been very difficult to automate. Since semi-preg fabrics have a lower fibre volume and also do not allow the fibre architecture of a part to be locally tailored, parts manufactured using fabrics normally have lower mechanical properties compared to parts manufactured using pre-preg tapes.

B.2.3   Sheets

Reinforced thermoplastic laminate sheets are fully impregnated and consolidated flat sheets that are available in sizes up to 3660 mm × 1220 mm (Royal TenCate, 2013) with varying ply thickness. These sheets are typically manufactured by consolidating unidirectional pre-preg tapes or semi-preg fabrics in a press at high temperatures and pressures. An example of a reinforced thermoplastic laminate sheet is shown in figure 67.

Due to the fully consolidated nature of this material form and the ability to cut the laminate sheet to size and shape, higher manufacturing rates are possible compared to both unidirectional tapes and fabrics. These sheets are normally manufactured into parts using forming technologies (detailed in section B3.3). Therefore, no layup of material is required which translates into lower labour content, higher manufacturing rates and higher production volumes.

Limitations of reinforced thermoplastic laminates include its constant thickness and limited size. Therefore, a secondary stage will be necessary should a part with variable thickness or localised reinforcement be required.

B.2.4 Moulding Compounds

Bulk Moulding Compounds (BMCs) are available in either billet form or as chopped filaments. The former is produced by blending chopped fibres and a thermoplastic matrix in a ribbon blender which is then formed into a round billet with a diameter of 25 mm to 50 mm using an extrusion process. The chopped filament form is normally produced by slitting and chopping thermoplastic unidirectional pre-preg tapes into 6 mm to 50 mm loose chopped filaments. Figure 67 shows an example of a BMC in chopped filament form.

BMCs are normally used in moulding operations and are capable of flowing in the mould cavity. This ability to flow has two advantages. Firstly, composite parts with more complex geometries can be fabricated since, when heated, the liquid composite material is able to flow and conform to small, intricate geometries and, secondly, higher volume production with shorter cycle times are possible since no layup of material is required.

Due to the discontinuous fibres and the low fibre weight fraction (~10-25 vf%) of BMCs, the mechanical properties, such as tensile strength and tensile modulus, of parts manufactured from BMCs are much lower when compared to parts manufactured using unidirectional tapes, semi-preg fabrics or reinforced thermoplastic laminates and are, therefore, normally not suitable for use in structural parts such as an aircraft seat pan that require high mechanical properties mandated by safety requirements. Therefore, BMC and the associated compression forming technologies will not be considered further on since they yield parts with insufficient mechanical performance.

B.3 Automated Manufacturing Processes of Thermoplastic Fibre-Reinforced Composite Parts

There are numerous processing technologies available for manufacturing FRC products (Harper, 2004; Pereira et al., 2012; Alauddin & Choudhury, 1995). The manufacturing technologies required are normally a function of the raw materials used (inputs) and the design needs of the required composite products (outputs) (Harper, 2004) which are normally determined from customer or market requirements.

In this section, various existing automated layup and forming processes are explored. These processes have been constrained by the material forms reviewed in the previous section. Therefore, only the automated layup and forming of prepreg materials (prepreg tape, semi-preg fabrics and reinforced thermoplastic laminates) will be considered, while 'wet' layup techniques in which the reinforcement is impregnated in-process in a polymer matrix are excluded.

B.3.1 Tape Laying Technologies

Automated Tape Laying (ATL) and Automated Fibre Placement (AFP) machines were the first attempts at automating the tape laying process (Lukaszewics et al., 2012). Both machines typically consist of a gantry structure (figure 68) with a cross-

feed bar that moves on the parallel rails of the gantry and a tape-deposition head (figure 69) mounted on a ram bar that can raise and lower the head during layup. Both machines use unidirectional pre-preg tape for layup and can deposit the material directly onto a contoured mould or a flat surface. The main difference between ATL and AFP machines lies in their end-effectors. ATL machines normally lay down relatively wide pre-preg tape of up to 300 mm, whereas AFP machines use a slitting unit that slits the tape into narrower tapes which enables the layup of more complex curvatures since steering of these narrower tapes is more easily achieved.

Figure 68: Automated tape laying machine (Tooling and Production, 2013).

The layup process starts by first heating the tape to its melting temperature just prior to placement using a heating source, such as an infrared lamp or a high-power laser, after which the deposition head places and consolidates the tape on the mould using a compaction roller. This deposition head continues to lay down a predetermined length of tape, called a course, after which the tape is cut using pinching blades. This process continues until the necessary number of courses have been laid down to form the composite structure.
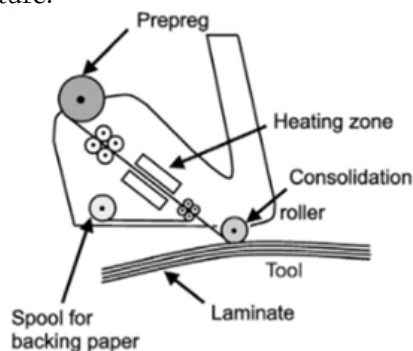
Figure 69: Schematic of an ATL head (Lukaszewics et al., 2012).

Compared to hand-layup, ATL/AFP machines are highly productive and reduce layup errors and material wastage rates. Lukaszewics *et al.* (2012) report that material wastage by ATL/AFP machines could be as high as 30%, while wastage rates of 50-100% were reported for hand-layup. Prepreg tapes up to 300 mm wide can be laid-up and at a maximum linear layup speed of 1 ms^{-1}. This represents a 65% reduction in layup time compared to hand-layup (Lukaszewics et al., 2012).

Besides the high layup rates, other advantages that the ATL/AFP machines offer include the ability to tailor the fibre placement and orientation leading to parts with

maximum strength-to-weight properties, the in-situ consolidation of a composite part negating the need for an expensive autoclave, the ability to manufacture large parts and the ability to handle relatively heavy materials. However, disadvantages of the ATL/AFP machines include high capital investment costs, the limited geometric complexity that can be laid-up and the large floor space that is required to house these machines.

The inability of the ATL/AFP machines to manufacture smaller, geometrically complex parts led to the development of new systems based on poly-articulated robots. Several flexible automated solutions for tape-layup have been developed (Shirinzadeh et al., 2004; Dell'Anno et al., 2012; Ahrens et al., 1998; Sorrentino et al., 2009) and all of them use an articulated robot, normally with up to 6DOF, with a specialized end-effector called a deposition head (figure 70) which operates and has similar components to that of the ATL deposition head shown in figure 69, albeit on a smaller scale. The flexibility of these automated solutions stems from their trajectory controllers and self-contained, modular tape-deposition heads.
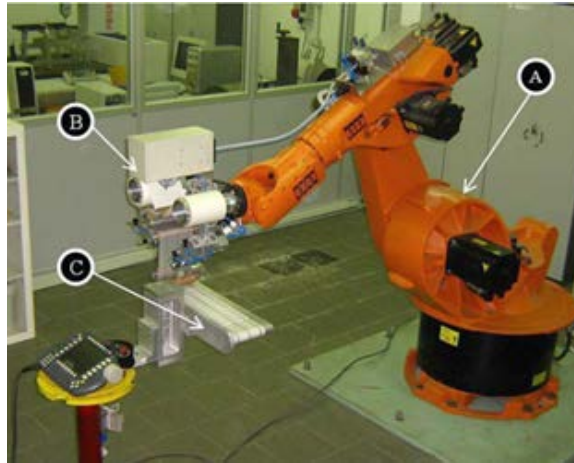
Figure 70: Tape laying robotic cell: (a) Articulated robot, (b) Tape-deposition head, (c) Deposition tool. (Sorrentino et al., 2009).

The trajectory controller enables the layup of tape onto any curved tool and therefore makes the manufacture of product variants possible. Significant research into trajectory controllers have been performed with most research focusing on simulation-based (Shirinzadeh et al., 2000; Shirinzadeh et al., 2007; Ahrens et al., 1998; Dell'Anno et al., 2012; Olsen & Craig, 1993) and sensory-based (Sorrentino et al., 2009; Shirinzadeh et al., 2004) path generation methods. In the simulation-based method, the path along which the robot has to lay-down the tape is derived from a model of the mould tool which is usually CAD-based. After the path has been derived, a simulation is carried out to verify the layup process and to check for possible errors that may occur. If the simulation is successful, the path is downloaded to the robot controller in its native language after which part layup is performed. In the sensory-based method, the start and end positions, direction of travel and compaction force of the tape-deposition head is first defined. Then, during layup, a sensor (usually a force sensor) is used to provide a feedback signal in order to

maintain the force applied by the tape-deposition head within some range of the initially defined compaction force.

Flexibility is also achieved through the modularity of the various components within the tape-deposition head. For example, for singly-curved moulds the compaction roller is normally a metal or rubber cylinder. These rollers can be interchanged, for example, to a roller with a smaller diameter to be able to handle geometries such as internal corners with small radii. In order to handle double-curvatures, a cylindrical roller is inadequate and, therefore, it can be interchanged with a spherical compaction roller.

The control approaches used by the researchers mentioned above for the control of a robotic tape-layup cell are sufficiently similar and therefore, for the purpose of illustrating the control approach used, a representative control system architecture, which can perform either sensory-based or simulation-based trajectory control, is presented in figure 71. The control architecture is hierarchically structured consisting of a cell controller, robot controller and tape-deposition head controller. Depending on the type of trajectory control, the cell controller either receives feedback signals from the various components on the tape-deposition head (for example force sensor, vision sensor, heat sensor etc.) or trajectory information in the form of data points from a remote computer. If sensory-based control is used, the cell controller calculates the control signals, based on the feedback signals, and sends them to the robot controller. However, if simulation-based control is used, the cell controller sends data points to the robot controller instead. Whichever signals are received by the robot controller, it uses it to control the motion of the robot. Finally, the tape-deposition head controller controls the various functions of the tape-deposition head (for example tape feeding, cutting, heating, etc.) based on various I/O signals from the robot controller.
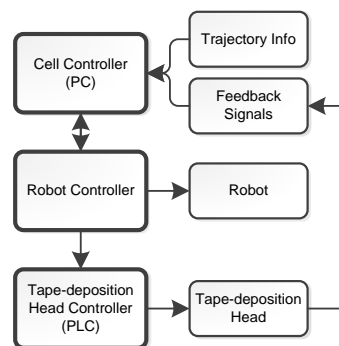
Figure 71: Representative hierarchical control system architecture for a robotic tape layup cell.

B.3.2   Fabric Laying Technologies

Technologies for the layup of fabrics have mainly been developed for thermoset based pre-preg and dry, resin-free fabrics. Although the physical properties of these materials differ from semi-preg fabrics, several aspects of these technologies can be adopted for the layup of thermoplastic semi-preg fabrics.

The manual layup of pre-preg fabric entails first cutting the fabric into plies of the required size and shape. These plies are then transferred, by hand, to the mould surface where they are placed in the right position and orientation. Hand tools, such as a non-stick roller and a stippling brush are subsequently used to apply pressure in order to remove air and to conform the material to the mould surface. This process is continued until the desired part thickness has been obtained. When the layup has been completed, a vacuum bag is placed over the part to be formed and placed in an autoclave where consolidation occurs under the application of heat and pressure. After consolidation, the finished part is removed and the process is repeated. This manual process is flexible in that parts with a wide range of shapes and sizes can be produced, since humans have the dexterity to adapt the layup of fabrics to various contours. However, this process is labour intensive and cycle times are low. Therefore, many attempts have been made to combine the flexibility and accuracy of the manual layup process with automated technologies to increase cycle times.

Several flexible automated work cells capable of manufacturing a variety of composite parts using pre-preg fabrics have been developed. These attempts are fairly similar in that they have identified four sub-systems that are required to realize such an automatic manufacturing cell. These are an automatic ply cutting system, a gripping and handling system, a layup and consolidation system and an inspection system.

A robotic ply layup work cell designed and built by Ruth & Mulgaonkar (1990) was one of the first attempts at a flexible system that could manufacture a broad class of composite parts. This work cell (figure 72) consists of three PUMA 560 industrial robots that are arranged around a common work area. The first robot is designated the transport robot since it has to first pick up pre-preg profiles from the input region and then transfer and place them on the mould in the layup region. This robot's end-effector is a vacuum gripper which consists of ten fingers, each with three degrees of freedom. Each finger consists of a flexible rubber bellow which is connected, via an air manifold, to a vacuum source. The second robot is designated the layup robot since it has to drape and consolidate the prepreg plies onto the mould surface. This robot's end-effector consists of a heating element and a squeegee made of Teflon which is used to smooth and consolidate the prepreg plies. The heating element is used to heat the prepreg plies in order to increase the compliance of the prepreg material and make the consolidation task of the Teflon squeegee easier. Consolidation trajectories are derived from using a computer generated model of the mould surface. Finally, the third robot is designated the inspection robot and is equipped with a wrist-mounted CCD camera. The purpose of this robot is to visually guide the placement of the pre-preg plies, by the transfer robot, onto the mould surface by aligning index marks placed on the pre-preg profiles and the mould surface.
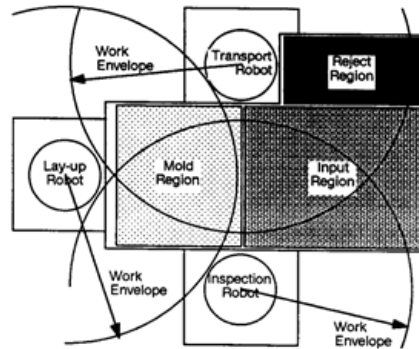
Figure 72: Schematic top view of robotic ply layup work cell developed by Ruth and Mulgaonkar (1990).

The work cell is controlled from a VAX-8600 computer which functions as the supervisory control system for the three Unimation VAL robot controllers (figure 73). It also controls all components on the end-effectors and performs the vision processing of the CCD cameras. Therefore, this work cell uses a centralised control architecture.

The work cell exhibits various characteristics, especially on a machine level, that enable the cell to adapt to product variants. For example, the multi-finger ply acquisition end-effector is adaptable to transfer any size and shape pre-preg ply within a product family since different grasp configurations can be selected by adjusting the locations of the vacuum grippers. In order to drape and consolidate different profiles, the Teflon squeegee can be automatically interchanged from selecting one of several squeegees available from a tool caddy. Similar to the robotic tape-layup cell discussed in the previous section, the layup robot is also able to adapt to different mould contours since surface modelling enables the end-effector to follow different layup trajectories enabling it to adapt its drape and consolidation ability.
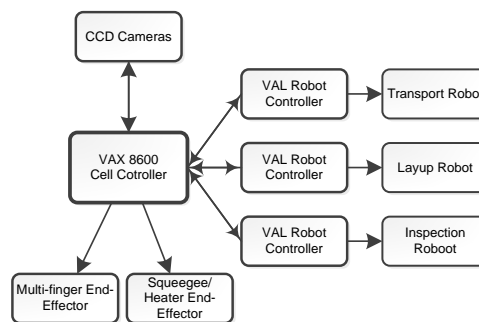
Figure 73: Centralised control system architecture used to control the ply layup work cell developed by Ruth and Mulgaonkar (Ruth & Mulgaonkar, 1990).

There are several aspects of this work cell which may negatively affect cycle times of the system and the complexity of the parts which may be formed. The first aspect which, apart from making the system heavily dependent on human input, may limit the cycle times of the system is the lack of an automated cutting system. Since pre-

cut profiles have to be presented, by hand, to the system at the input region, it may increase cycle times as a result of possible delays caused by human error. The manual adjustment of the vacuum grippers on the ply acquisition end-effector of the transfer robot may also severely limit the achievable cycle times since the whole system needs to be stopped in order to adjust the grippers to an alternate configuration when profiles with different sizes or shapes needs to be laid-up. Since the layup robot uses a squeegee, it is assumed that complex, double curvature surfaces cannot be laid-up. This may be confirmed by the fact that Ruth and Mulgaonkar only tested their system with a developable, singly curved mould.

Buckingham and Newell (1996) also developed a flexible robotic ply layup work cell (figure 74) which addressed many of the limitations of the system developed by Ruth and Mulgaonkar. Similar to the work cell developed by Ruth and Mulgaonkar, this work cell includes a transfer stage, visual inspection stage and a layup and consolidation stage. However, this work cell also includes an automated cutting stage. This stage consists of a cutting table which receives prepreg fabric from a reel and an automated cutting machine to cut pre-preg profiles to shape and size. In order to transfer pre-preg profiles with a variety of shapes from the cutting table to the mould tool, Buckingham and Newell adopted a gantry system which uses four Cartesian arms, each having two or three orthogonal linear motions, with two further joints at each end-effector which uses vacuum grippers to grip the pre-preg profiles. In order to be able to adapt to a range of curvatures for different mould shapes and for consolidation of different parts of a profile, Buckingham and Newell adopted an automatic tool changing device which houses rollers ranging from cylindrical rollers for flat and single curvature profiles to spherical rollers for double curvature profiles.
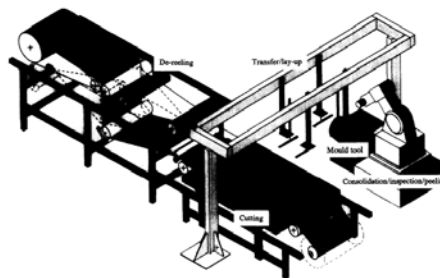
Figure 74: Ply layup work cell developed by Buckingham and Newell (Buckingham & Newell, 1996).

The layup and in-situ consolidation of pre-preg fabrics on a 3D mould represents a complex process, often with unacceptably slow cycle times. In order to try and reduce cycle times, several attempts at a flexible work cell that automatically drapes dry, resin-free fabrics onto a mould surface with a subsequent resin impregnation technique, such as Resin-Transfer-Moulding or Vacuum Infusion, exist. These attempts are similar to the work cells discussed above in that they also have an automated cutting, transfer, layup and visual inspection stage. However, in order to ensure that plies do not move relative to one another during resin infusion, a method of bonding the plies to one another is required. Therefore, these work cells normally also include a robotic tacking stage. Several notable attempts at a flexible automated work cell include Sarhadi (1993) who describes a flexible robotic work cell which

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manufactures aircraft blade preforms from dry fabrics. Mitchell *et al.* (1994), Zhang & Sarhadi (1996) and Chestney & Sarhadi (1996) also describe fully automated manufacturing cells capable of manufacturing carbon fibre composite aerospace components. Other notable attempts include Kordi *et al.* (September 2007), and Angerer *et al.* (2011).

Although the draping and in-situ consolidation of pre-preg fabrics and the resin infusion of dry fabric preforms have been successfully automated, these processes require long cycle times and have, often, not been able to yield parts with satisfactory mechanical properties. To overcome these limitations, some researchers and manufacturers first press-consolidate semi-preg or pre-preg fabrics into a flat laminate sheet after which a thermoforming stage is used to form the required part (Hou et al., 1998). Automated sheet forming technologies are discussed in the next section.

B.3.3 Sheet Forming Technologies

The use of Reinforced Thermoplastic Laminate (RTL) sheets has become attractive in industry since these materials promise higher manufacturing rates compared to tape and fabric laying technologies. This is because these sheets are supplied fully consolidated which allows them to be formed quickly into their target shape.

The manufacture of FRC parts using RTL's normally requires several stages as shown in figure 75.
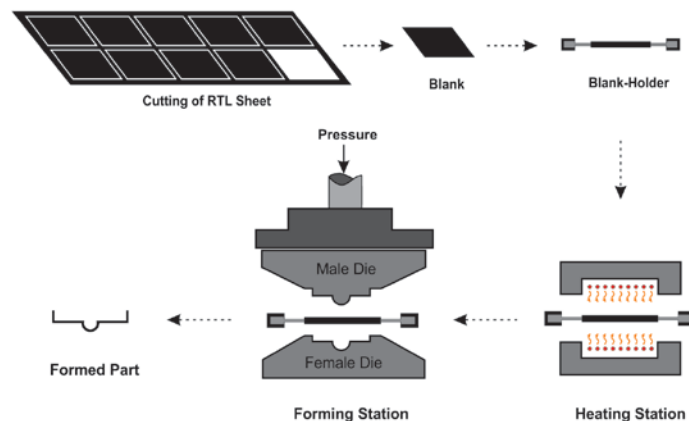
Figure 75: Manufacturing process of FRCs using RTLs.

Since RTL's are supplied in large sheets, as described in section B.2.3, the first stage is to cut the sheet to the required shape and size. Mechanical or water jet cutting is usually used to accomplish this operation. This cut sheet is called a blank. The blank is then fixed into a clamping frame, called a blank-holder, which applies biaxial tensile forces on the blank to prevent wrinkling during forming. This blank-holder is then passed through a heating station where the blank is preheated to a temperature above the melt temperature T_m of the thermoplastic matrix. Preheating is mostly done using infrared (IR) heating banks, convection ovens or heated platen presses.

The fixture is then passed to a forming station where the composite part is formed to the shape of a mould tool and subsequently cooled below the glass transition temperature T_g of the thermoplastic matrix. The forming of the part can be done by using any derivative of the thermoforming family of processes such as Matched Metal-die Forming, Rubber-die Forming, Vacuum Forming, Diaphragm Forming, etc. (Mallon & Obradaigh, 2000). Finally, after the part has been formed, the blank-holder is removed from the forming station and the finished part is subsequently removed from the blank holder.

The thermoforming process is conventionally achieved using the shuttle press method (Figure 76 (a)). In this method, a heater is placed in line with a press and uses a frame to fix and transport a sheet between the heater and press. The process starts of by fixing a pre-cut sheet horizontally into a frame using either hooks and springs or pneumatic clamps. This frame is then transported and passed through a heating station where the blank is preheated to a temperature above the melt temperature of the thermoplastic matrix. The frame is then shuttled to a press where the sheet is formed to the shape of a mould tool and subsequently cooled under pressure below the glass transition temperature of the thermoplastic matrix. Finally, after the part has been formed, the finished part is removed from the frame and the process is repeated. In this process, the total time to manufacture a part comprises the heating time plus the forming time. This process is very inefficient in terms of cycle times since the heating and forming phases occurs independently. In order to increase the efficiency, a second oven can be added (Figure 76 (b)). In this setup, a frame is used which can fix two sheets, side by side. The process operates similarly as described above, however it enables one sheet to be heated while another sheet is being formed.
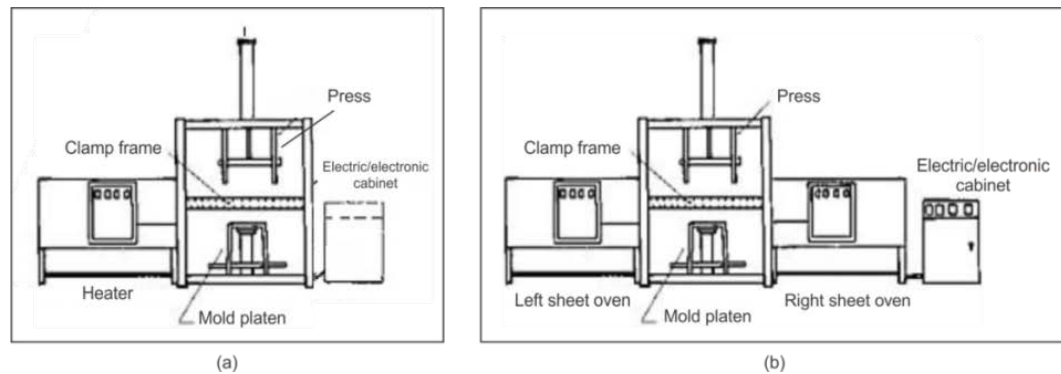
Figure 76: Side views of (a) Single-oven shuttle press. (b) Double-oven shuttle press. (Adapted from Throne (1996)).

As described in section B.2.3, only uniform thickness parts can be manufactured using RTL's. Therefore, should a part require local reinforcements mandated by mechanical or safety requirements, an intermediate stage is included in order to add these reinforcements. The addition of local reinforcements is an active area of research and several successful attempts have been reported in the literature (Grouve et al., 2012; Wakeman et al., 2009; Howell et al., 2013).

For example, Grouve *et al.* (2012) used a laser assisted tape placement process to weld pre-preg unidirectional tape on a pre-consolidated flat laminate sheet. The tape placement was performed by a six degree-of-freedom robot. The robot's end-effector was a tape placement head which consisted of a flexible compaction roller, a heat sensitive camera, a tape feeding mechanism and a diode laser. The diode laser was used to heat the tape and laminate; the camera monitored the temperature of the laminate and was used as feedback to control the laser power and the compaction roller was used to apply pressure and consolidate the tape and laminate. In order to compare the mechanical properties of the specimens produced by this in-situ process, Grouve *et al.* also reinforced flat laminate sheets by simply placing unidirectional tape on top of the laminate and using a press to consolidate the tape to the laminate. It was not reported whether displacement of the reinforcing tape was observed or whether a method was required to prevent displacement. Howell *et al.* (2013) reported that using a cover or close-out ply prevents locally reinforced material from being displaced or pushed out of position during stamp forming, while Bersee *et al.* (2006) simply used an ultrasonic pistol to manually spot weld small reinforcing laminates onto a base laminate prior to forming. They also reported that this was sufficient to accurately hold the local reinforcements in place during the forming process.

Limited research into the automation of the process shown in figure 75 has been conducted, with most researchers using manual processes with the aim to determine the effect of different processing conditions on the mechanical properties of different thermoplastic structural parts (Hou et al., 1998; McCool et al., 2011; Díaz & Rubio, 2003; Friedrich & Hou, 1998). To the knowledge of the author, most research into automating the process has been focused on controlling the process parameters of the heating and thermoforming stages with little focus given to the manual handling tasks such as the transportation and fixturing of a blank into a blank-holder. Flexibility has also rarely been a driver in the design of these automated solutions. However, some researchers have tried to find flexible automated solutions for manufacturing thermoplastic FRC parts using RTLs.

For example, in order to accommodate part families with similar, but not identical geometries, Herrmann & Purol (2006) at the Faserinstitut in Bremen developed a flexible blank-holder with moveable flanges (figure 77) primarily for press-forming brackets used in aircraft.
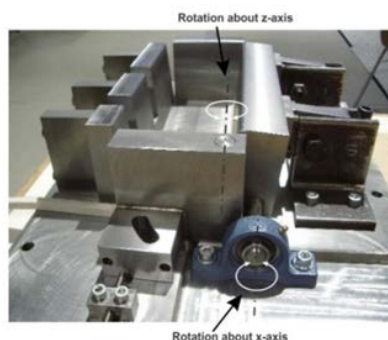
Figure 77: Flexible tool for thermoforming with movable flanges (Herrmann & Purol, 2006).

Premium AEROTEC in Bremen currently produces more than 2500 different clips made from thermoplastic composite materials for the Airbus A350 XWB airplane (Deterts et al., 2012). To minimize tooling costs, the company developed flexible blank holders to accommodate the different clip geometries.

In order to manufacture these clips, Premium AEROTEC developed a semi-automated five stage process (figure 78) which includes the high speed cutting, pre-heating, stamp forming, trimming and ultrasonic inspection of the clips. Firstly, blanks are cut to size by a milling process after which they were manually fixed into a blank holder and manually transported and placed onto a pick-up table. This table used sensors to signal an articulated six degree-of-freedom robot to pick up the blank-holder. The blank-holder was then picked up by the robot from the table and transported to the heating station and subsequently to the forming station. After forming, the robot removed the blank-holder from the forming station after which the formed part was manually removed from the blank-holder and transported to the trimming and inspection stations.
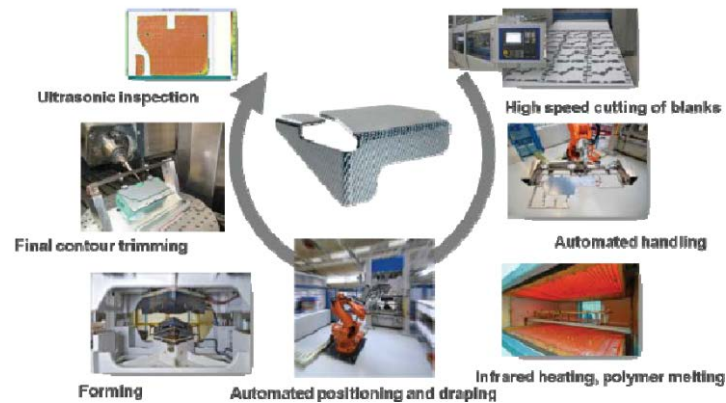
Figure 78: Automated process by Premium AEROTEC to form thermoplastic clips (Deterts et al., 2012).

Delaloye & Niedermeier (1995) developed an automated diaphragm forming machine which continually controlled the forming temperature and pressure with the aim of achieving repeatable quality over series production and to optimise the efficiency of the pre-heating process in order to achieve shorter heat-up times of the thermoplastic laminate. The diaphragm machine used a two-axis handling system that automatically placed the laminate on the forming table, however, the laminates still had to be manually placed into this handling system. The process parameters and handling tasks of the system were all controlled via a single cell computer and therefore used a centralized control approach.

Appendix C : Analytical Hierarchy Process Comparison Matrices and Priority Vectors

C.1   Pairwise Comparison Matrices

	Manufacturing Performance Requirements	Part Geometry Requirements	Manufacturing Constraints
Manufacturing Performance Requirements		7.0	3.0
Part Geometry Requirements			5.0
Manufacturing Constraints	Incon: 0.06		

	Curvature	Local-Reinforcements	Size
Curvature		3.0	7.0
Local-Reinforcements			3.0
Size	Incon: 0.01		

	Equipment Cost	Material Cost	Expertise
Equipment Cost		2.0	5.0
Material Cost			7.0
Expertise	Incon: 0.01		

	Pre-preg Tape / ATL or AFP	Pre-preg Tape / Robotic Layup	Semi-preg Fabric / Robotic Layup	Reinforced Thermoplastic Laminates / Thermoforming
Pre-preg Tape / ATL or AFP		2.0	2.0	6.0
Pre-preg Tape / Robotic Layup			1.0	4.0
Semi-preg Fabric / Robotic Layup				4.0
Reinforced Thermoplastic Laminates / Thermoforming	Incon: 0.06			

	Pre-preg Tape / ATL or AFP	Pre-preg Tape / Robotic Layup	Semi-preg Fabric / Robotic Layup	Reinforced Thermoplastic Laminates / Thermoforming
Pre-preg Tape / ATL or AFP		3.0	3.0	7.0
Pre-preg Tape / Robotic Layup			5.0	5.0
Semi-preg Fabric / Robotic Layup				9.0
Reinforced Thermoplastic Laminates / Thermoforming	Incon: 0.06			

	Pre-preg Tape / ATL or AFP	Pre-preg Tape / Robotic Layup	Semi-preg Fabric / Robotic Layup	Reinforced Thermoplastic Laminates / Thermoforming
Pre-preg Tape / ATL or AFP		1.0	1.0	7.0
Pre-preg Tape / Robotic Layup			1.0	7.0
Semi-preg Fabric / Robotic Layup				7.0
Reinforced Thermoplastic Laminates / Thermoforming	Incon: 0.00			

	Pre-preg Tape / ATL or AFP	Pre-preg Tape / Robotic Layup	Semi-preg Fabric / Robotic Layup	Reinforced Thermoplastic Laminates / Thermoforming
Pre-preg Tape / ATL or AFP		3.0	5.0	5.0
Pre-preg Tape / Robotic Layup			3.0	3.0
Semi-preg Fabric / Robotic Layup				3.0
Reinforced Thermoplastic Laminates / Thermoforming	Incon: 0.07			

	Pre-preg Tape / ATL or AFP	Pre-preg Tape / Robotic Layup	Semi-preg Fabric / Robotic Layup	Reinforced Thermoplastic Laminates / Thermoforming
Pre-preg Tape / ATL or AFP		8.0	7.0	5.0
Pre-preg Tape / Robotic Layup			2.0	5.0
Semi-preg Fabric / Robotic Layup				3.0
Reinforced Thermoplastic Laminates / Thermoforming	Incon: 0.05			

	Pre-preg Tape / ATL or AFP	Pre-preg Tape / Robotic Layup	Semi-preg Fabric / Robotic Layup	Reinforced Thermoplastic Laminates / Thermoforming
Pre-preg Tape / ATL or AFP		1.0	1.0	3.0
Pre-preg Tape / Robotic Layup			1.0	3.0
Semi-preg Fabric / Robotic Layup				3.0
Reinforced Thermoplastic Laminates / Thermoforming	Incon: 0.00			

	Pre-preg Tape / ATL or AFP	Pre-preg Tape / Robotic Layup	Semi-preg Fabric / Robotic Layup	Reinforced Thermoplastic Laminates / Thermoforming
Pre-preg Tape / ATL or AFP		5.0	5.0	7.0
Pre-preg Tape / Robotic Layup			1.0	3.0
Semi-preg Fabric / Robotic Layup				3.0
Reinforced Thermoplastic Laminates / Thermoforming	Incon: 0.03			

Figure 79: Pairwise comparison matrices indicating the relative importance of all variables.

C.2   Priority Vectors

Manufacturing Performance Requirements .649

Part Geometry Requirements .072

Manufacturing Constraints .279

Inconsistency = 0.06
    with 0 missing judgments.

Curvature .669

Local-Reinforcements .243

Size .088

Inconsistency = 0.00669
    with 0 missing judgments.

Equipment Cost .333

Material Cost .592

Expertise .075

Inconsistency = 0.01
    with 0 missing judgments.

Pre-preg Tape / ATL or AFP .172

Pre-preg Tape / Robotic Layup .110

Semi-preg Fabric / Robotic Layup .110

Reinforced Thermoplastic Laminates / Thermoforming .607

Inconsistency = 0.06
    with 0 missing judgments.

Pre-preg Tape / ATL or AFP .094

Pre-preg Tape / Robotic Layup .203

Semi-preg Fabric / Robotic Layup .046

Reinforced Thermoplastic Laminates / Thermoforming .657

Inconsistency = 0.06
    with 0 missing judgments.

Pre-preg Tape / ATL or AFP .318

Pre-preg Tape / Robotic Layup .318

Semi-preg Fabric / Robotic Layup .318

Reinforced Thermoplastic Laminates / Thermoforming .045

Inconsistency = 0.
    with 0 missing judgments.

Pre-preg Tape / ATL or AFP .549

Pre-preg Tape / Robotic Layup .248

Semi-preg Fabric / Robotic Layup .129

Reinforced Thermoplastic Laminates / Thermoforming .074

Inconsistency = 0.07
    with 0 missing judgments.

Pre-preg Tape / ATL or AFP .043

Pre-preg Tape / Robotic Layup .517

Semi-preg Fabric / Robotic Layup .306

Reinforced Thermoplastic Laminates / Thermoforming .134

Inconsistency = 0.05
    with 0 missing judgments.

Pre-preg Tape / ATL or AFP .300

Pre-preg Tape / Robotic Layup .300

Semi-preg Fabric / Robotic Layup .300

Reinforced Thermoplastic Laminates / Thermoforming .100

Inconsistency = 0.
    with 0 missing judgments.

Pre-preg Tape / ATL or AFP .052

Pre-preg Tape / Robotic Layup .210

Semi-preg Fabric / Robotic Layup .210

Reinforced Thermoplastic Laminates / Thermoforming .528

Inconsistency = 0.03
    with 0 missing judgments.

Figure 80: Priority vectors of all criteria calculated from the pairwise comparison matrices in figure 79.

Appendix D : Engineering Drawings

D.1   Manifold

ITEM	BESKRYWING	AANTAL	MATERIAAL / SPESIFIKASIES
13	FESTO CYLINDER	1	30x150
12	FESTO L-FITTING	2	
11	BMG O-RING	8	1.78 x 5.28
10	FESTO PILOTED NON-RETURN VALVE	4	HGL-M5-B
9	FESTO PUSH-IN FITTING	12	QSMF-M5-4
8	BOSCH 30mm BRACKET	1	
7	GUIDE PLATE	1	M-PRT-007
6	GUIDE ROD	1	M-PRT-006
5	ROD COUPLING	1	M-PRT-001
4	COUPLING	8	M-PRT-003
3	MATING PLATE	1	M-PRT-002
2	MANIFOLD CHAMBER	1	M-PRT-005
1	MOUNT PLATE	1	M-PRT-004

SKAAL OP A
MATE IN mm

TITEL: Manifold

DATUM

VEL No. 1   VAN   1 VELLE

UNLESS OTHERWISE STATED
TOLERANCES ± 0,1
ANGLES 1`

UNIVERSITEIT VAN STELLENBOSCH

STUDENTE No. 15490289   TEKENAAR M CLAASSEN   NAGESIEN

VEL No. 1   VAN   1 VELLE

No. M-ASSY-001

D.2   Clamp

ITEM	BESKRYWING	AANTAL	MATERIAAL / SPESIFIKASIES
8	Hinge Rod (Long)	1	CL-PRT-007
7	Lower Jaw	1	CL-WLD-002
6	Upper Jaw	1	CL-WLD-001
5	Cylinder Bracket	1	CL-WLD-005
4	Hinge Rod (Short)	1	CL-PRT-008
3	Link	1	CL-PRT-006
2	Cylinder Hinge Shaft	2	CL-PRT-005
1	Cylinder Support Bracket	1	CL-WLD-003

SKAAL OP A
MATE IN mm
DATUM

TITEL: CLAMP TYPE 1

VEL No. 1   VAN 1 VELLE

No. CL-ASSY-001

UNLESS OTHERWISE STATED
TOLERANCES ± 0,1
ANGLES 1'

UNIVERSITEIT VAN STELLENBOSCH

STUDENTE No. 15490289   TEKENAAR M CLAASSEN   NAGESIEN

200

214

115
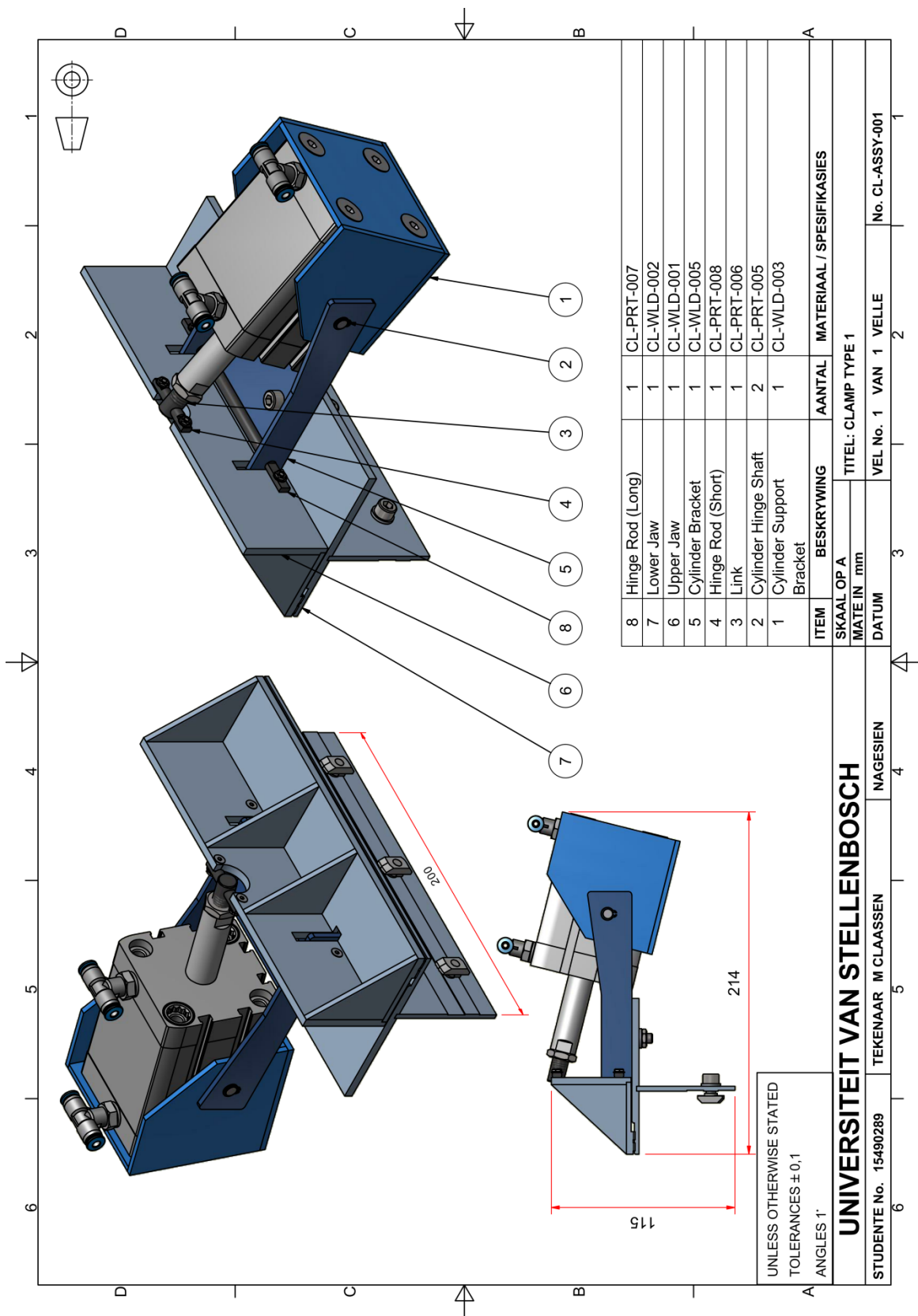
D.3   Jig
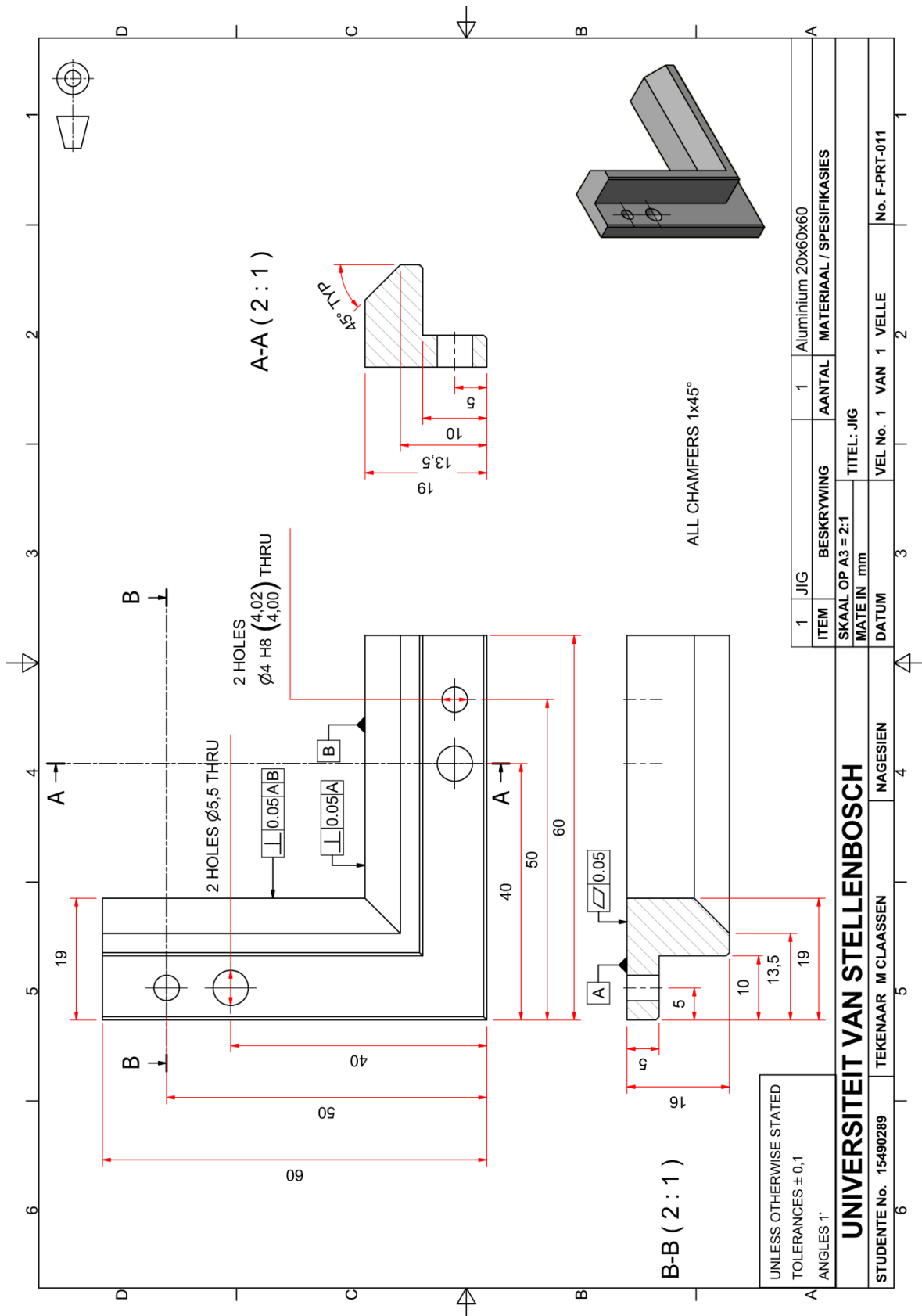
D.4 Frame Pick-up Mechanism
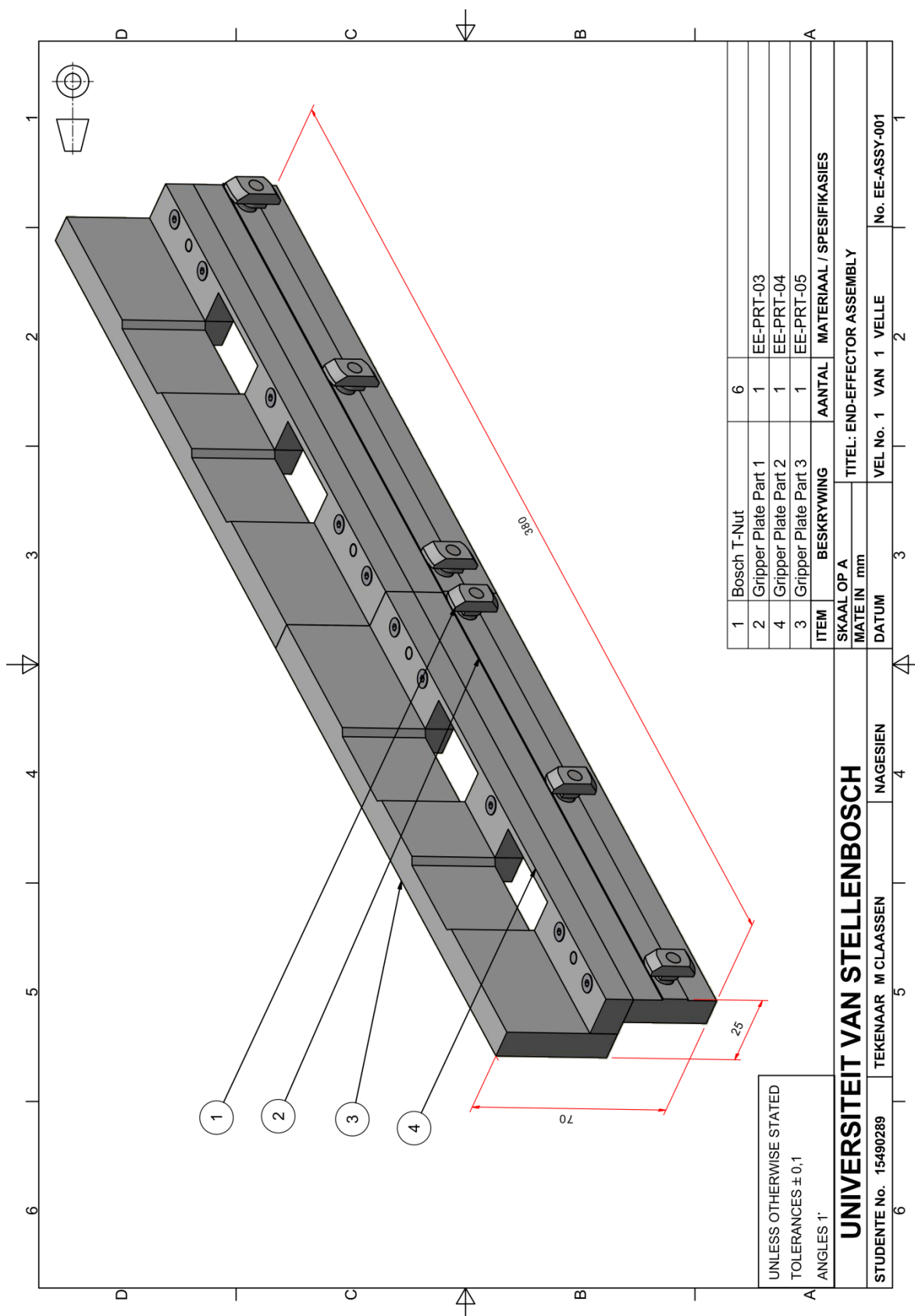
ITEM	BESKRYWING	AANTAL	MATERIAAL / SPESIFIKASIES
1	Bosch T-Nut	6	
2	Gripper Plate Part 1	1	EE-PRT-03
4	Gripper Plate Part 2	1	EE-PRT-04
3	Gripper Plate Part 3	1	EE-PRT-05

SKAAL OP A
MATE IN mm

TITEL: END-EFFECTOR ASSEMBLY

VEL No. 1 VAN 1 VELLE   **No. EE-ASSY-001**

DATUM	NAGESIEN	TEKENAAR M CLAASSEN

UNIVERSITEIT VAN STELLENBOSCH

STUDENTE No. 15490289

UNLESS OTHERWISE STATED
TOLERANCES ± 0,1
ANGLES 1°

108

D.5 Mating Plate
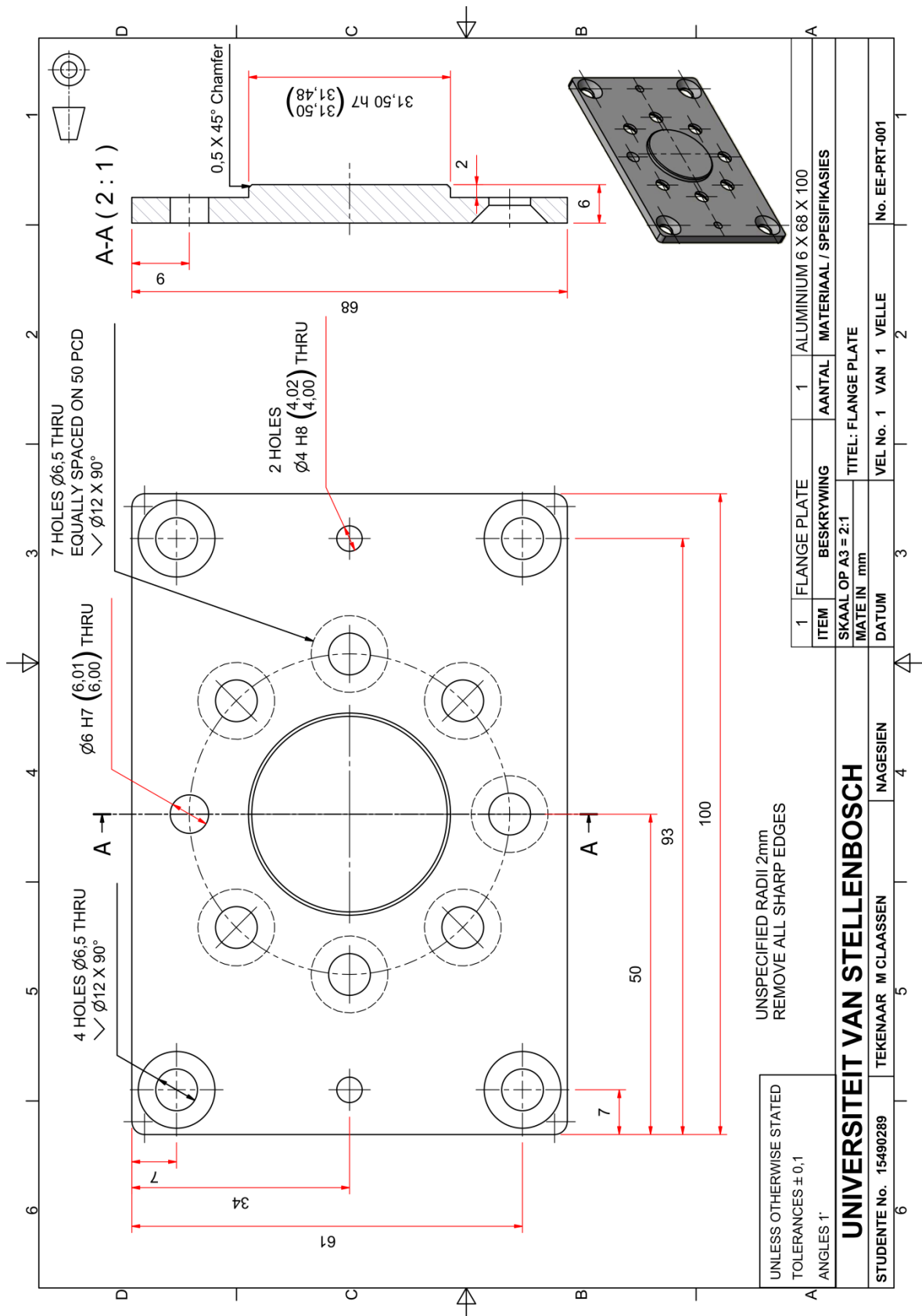
D.6   End-Effector
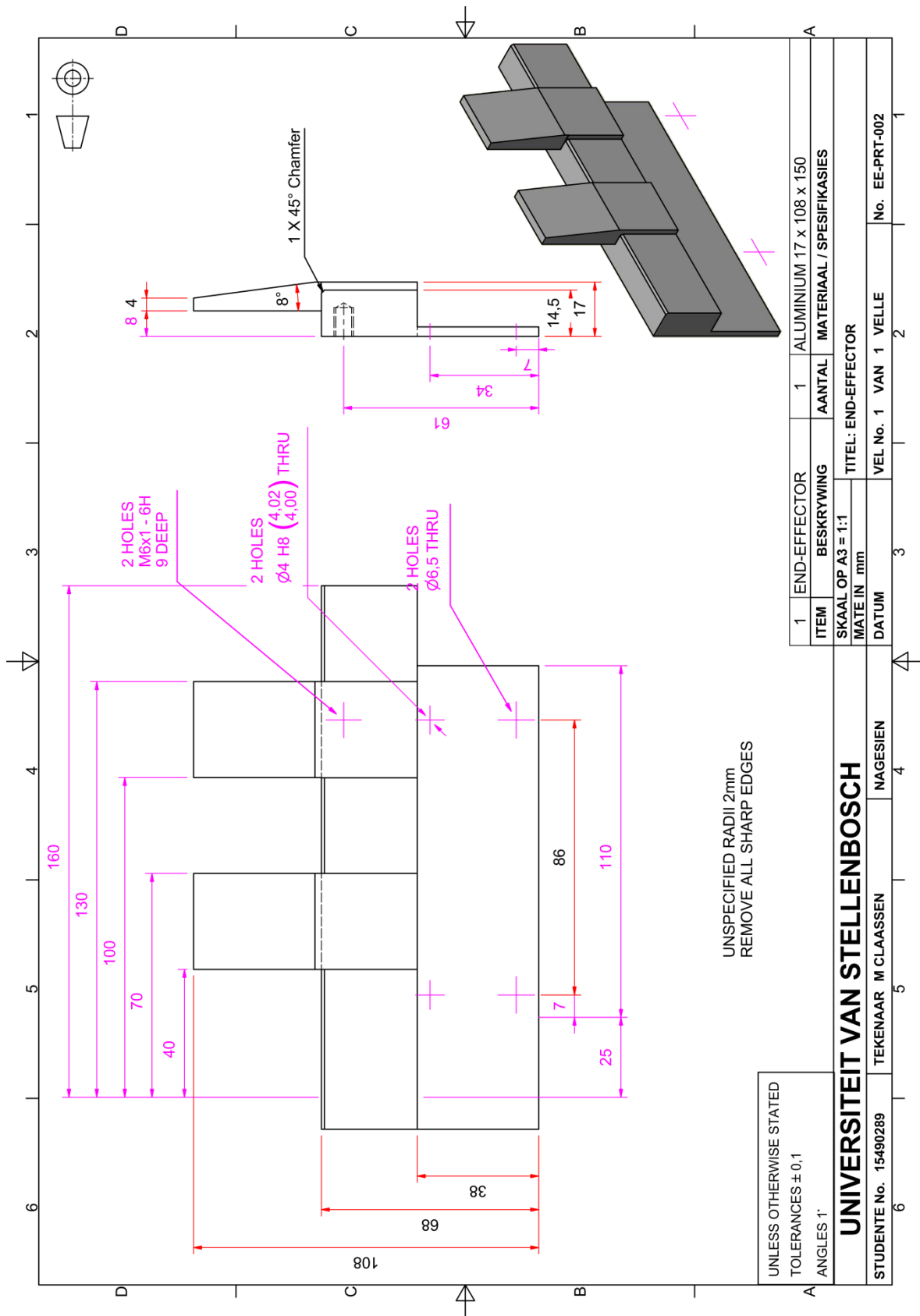
Appendix E : Agent Services

E.1   Operational Agent Services

Agent Name	Service Name	
Loading/Unloading Station Agent	i.	CLAMP
	ii.	UNCLAMP
Transport Robot Agent	i.	TRANSPORT_LU1_2_RU
	ii.	TRANSPORT_LU2_2_RU
	iii.	TRANSPORT_LU3_2_RU
	iv.	TRANSPORT_LU1_2_HU
	v.	TRANSPORT_LU2_2_HU
	vi.	TRANSPORT_LU3_2_HU
	vii.	TRANSPORT_RU_2_HU
	viii.	TRANSPORT_HU_2_FU
	ix.	TRANSPORT_FU_2_LU1
	x.	TRANSPORT_FU_2_LU2
	xi.	TRANSPORT_FU_2_LU3
Reinforce Station Agent	i.	REINFORCE
Heat Station Agent	i.	HEAT
Press Station Agent	i.	PRESS

List of References

Abrate, S. & Walton, D., 1992. Machining of Composite Materials. Part II: Non-Traditional Methods. *Composites Manufacturing*, Vol. 3(2), pp.85-94.

Ahrens, M., Mallick, V. & Parfrey, K., 1998. Robot-Based Thermoplastic Fibre Placement Process. *Industrial Robot*, Vol. 25(5), pp.326-330.

Air Washington, 2014. *Quality Assurance and Nondestructive Evaluation of Composite Materials*. [Online] Air Washington Available at: http://goo.gl/zJEUKK [Accessed 02 November 2014].

Alauddin, M. & Choudhury, I.A., 1995. Plastics and their Machining: A Review. *Journal of Materials Processing Technology*, Vol. 54(44), pp.40-46.

Alongi, M.P., 2004. *The Plastics Distributor and Fabricator*. [Online] Available at: http://www.plasticsmag.com/thermoforming.asp?fIssue=Jul/Aug-04&aid=4040 [Accessed 21 April 2014].

Amancio-Filho, S.T., Roerder, J., Nunes, S.P., dos Santos, J.F. & Beckhann, F., 2008. Thermal degradation of polyetherimide joined by friction riveting (FricRiveting). Part I: Influence of rotation speed. *Polymer degradation and stability*, Vol. 93(8), pp.1529-538.

Angelis, D.I. & Lee, C.Y., 1996. Strategic Investment Analysis using Activity Based Costing Concepts and Analytical Hierarchy Process Techniques. *International Journal of Production Research*, Vol. 34(5), pp.1331-345.

Angerer, A., Ehinger, C., Hoffmann, A., Reif, W. & Reinhart, G., 2011. Design of an Automation System for Preforming Processes in Aerospace Industries. In *2011 IEEE Conference on Automation Science and Engineering*. Trieste, Italy, 2011.

Apodius, 2014. *Apodius Vision System*. [Online] Apodius Available at: http://apodius.de/wp-content/uploads/2013/04/apodius_vision_system_brochure.pdf [Accessed 03 November 2014].

Arbel, A. & Orgier, Y.E., 1990. An Application of the AHP to Bank Strategic Planning: The Mergers and Acquisitions Process. *European Journal of Operational Research*, Vol. 48(1), pp.27-37.

Army Armament Research Development and Engineering Center, 1991. *Plastic Matrix Composites with Continuous Fiber Reinforcement*. 1st ed. Washington: United States Department of Defence. p.2.

Askin, R.G. & Estrada, S., 1999. Investigation of Cellular Manufacturing Practices. A.I. Shahrukh, ed. *Handbook of Cellular Manufacturing Systems*. 1st ed. John Wiley & Sons. p.27.

Bădică, C., Budimac, Z., Burkhard, H.D. & Ivanovic, M., 2011. Software Agents: Languages, Tools, Platforms. *Computer Science and Information Systems*, Vol. 8(1), pp.255-298.

Bazargan-Lari, M., 1999. Layout Design for Cellular Manufacturing Systems. A.I. Shahtukh, ed. *Handbook of Cellular Manufacturing Systems*. 1st ed. John Wiley & Sons. p.2.

Beckhoff, 2013. [Online] Available at: http://infosys.beckhoff.com/english.php?content=./content/1033/tcjavatoads/html/tcjavatoads_intro.html&id= [Accessed 19 June 2014].

Bellifemine, F. & Caire, G., 2000. *JAVA Agent Development Framework*. [Online] Available at: http://jade.tilab.com/ [Accessed 20 September 2014].

Bellifemine, F., Caire, G. & Greenwood, D., 2007. *Developming Multi-Agent Systems with JADE*. 1st ed. John Wiley & Sons.

Bersee, H.E.N., Van Dongen, M. & Beukers, A., 2006. Thermoplastic Composite Technology Demonstrator. H.E.N. Bersee & F.N. Giovanni, eds. *CETEX. From Scratch to Flight*. Delft, The Netherlands. Ch. 2. pp.14-24.

Bhushan, N. & Rai, K., 2004. The Analytical Hierarchy Process. R. Roy, ed. *Strategic Decision Making: Applying the Analytical Hierarchy Process*. Cranfield, UK: Springer. p.11.

Bi, Z.M., Lang, S.Y.T., Shen, W. & Wang, L., 2008. Reconfigurable Manufacturing Systems: The State of the Art. *International Journal of Production Research*, Vol. 46(4), pp.967-992.

Birch, A., 2009. *Thin Metal Cladding is the Shape of Things to Come*. [Online] Available at: http://www.bdonline.co.uk/thin-metal-cladding-is-the-shape-of-things-to-come/3151987.article [Accessed 16 October 2014].

Bogue, R., 2010. The Role of Robotics in Non-Destructive Testing. *Industrial Robot: An International Journal*, Vol. 37(5), pp.421-426.

Bosch Rexroth, 2014. *TSplus Conveyors - Modular Conveyors for Flexible Manufacturing*. [Online] Available at: http://www.boschrexroth.com/en/us/products/product-groups/assembly-technology/conveyor-systems/ts-assembly-conveyors-overview/tsplus-conveyors/get-tsplus-conveyors-catalogs/index [Accessed 05 Novemeber 2014].

Botti, V. & Giret, A., 2008. Holons and Agents. *ANEMONA: A Multi-Agent Methodology for Holonic Manufacturing Systems*. London: Springer. p.22.

Brennan, R.W. & Norrie, D., 2001. Agents, Holons and Function Blocks: Distributed Intelligent Control in Manufacturing. *Journal of Applied Systems Studies*, Vol. 2(1), pp.1-19.

Buckingham, R.O. & Newell, G.C., 1996. Automating the Manufacture of Composite Broadgoods. *Composites Part A*, Vol. 27A(3), pp.191-200.

Bussman, S., Jennings, N.R. & Wooldridge, M., 2004. *Multiagent Systems for Manufacturing Control*. Berlin, Germany: Springer.

Bussmann, S., 1998. An Agent-Oriented Architecture for Holonic Manufacturing Control. In *Proceedings of the 1st Int Workshop on Intelligent Manufacturing Systems*. Lausanne, Switzerland, 1998.

Cabala, P., 2010. Using the Analytical Hierarchy Process in Evaluating Decision Alternatives. *Operations Research and Decisions*, Vol. 1(1), pp.1-23.

Cengel, Y.A. & Ghajar, A.J., 2011. Transient Heat Conduction. *Heat and Mass Transfer: Fundamentals and Applications*. 4th ed. New York: McGraw-Hill. p.228.

Cenna, A.A. & Mathew, P., 1997. Evaluation of Cut Quality of Fibre-Reinforced Plastics - A Review. *International Journal of Machine Tools and Manufacture*, Vol. 37(6), pp.723-736.

Chestney, J.A. & Sarhadi, M., 1996. Control and Integration Techniques in a Fully Automated Manufacturing Cell for Carbon Composites. *Control Theory and Applications*, Vol. 143(2), pp.159-163.

Christensen, J.H., 1994. Holonic Manufacturing Systems - Initial Architecture and Standards Directions. In *First European Conference on Holonic Manufacturing Systems*. Hannover, Germany, 1994.

Christensen, J.H., 2003. HMS/FB Architecture and its Implementation. S.M. Deen, ed. *Agent-Based Manufacturing - Advanced Information Processing*. Berlin, Germany: Springer. pp.53-87.

Collins, J.C., Ndumu, D.T., Nwana, H.S. & Lee, C., 1998. Zeus Agent Toolkit. *BT Technology Journal*, Vol. 16, pp.60-68.

Committee on Visionary Manufacturing Challenges, 1998. *Visionary Manufacturing Challenges for 2020*. The National Academies Press.

Dashchenko, A.I., 2006. General RMS Characteristics. Comparison with Dedicated and Flexible Manufacturing Systems. *Reconfigurable Manufacturing Systems and Transformable Factories*. 1st ed. Berlin: Springer Berlin Heidelberg. pp.27-45.

Delaloye, S. & Niedermeier, M., 1995. Optimization of the Diaphragm Forming Process for Continuous Fibre-Reinforced Advanced Thermoplastic Composites. *Composites Manufacturing*, Vol. 6(3-4), pp.135-144.

Delcam, 2014. [Online] Available at: http://www.delcam.com/ [Accessed 10 November 2014].

Dell'Anno, G., Partridge, I., Cartie, D., Hamlyn, A., Chehura, E., James, S. & Tatam, R., 2012. Automated Manufacture of 3D Reinforced Aerospace Composite Structures. *International Journal of Structural Integrity*, Vol. 3(1), pp.22-40.

Destaco, 2014. [Online] Available at: http://www.destaco.com/tool-changers-effectors.html [Accessed 05 November 2014].

Deterts, A., Miaris, A. & Soehner, G., 2012. Serial Production of Thermoplastic CFRP Parts for the Airbus A350 XWB. In *International Conference & Exhibition on Thermoplastic Composites*. Bremen, Germany, October 2012.

Dewhurst, P. & Blum, C., 1989. Supporting Analyses for the Economic Assessment of Diecasting in Product Design. *CIRP Annals - Manufacturing Technology*, Vol. 38(1), pp.161-164.

Díaz, J. & Rubio, L., 2003. Developments to Manufacture Structural Aeronautical Parts in Carbon Fibre Reinforced Thermoplastic Materials. *Journal of Materials Processing Technology*, Vol. 142-144, pp.342-346.

Dilts, D.M., Boyd, N.P. & Whorms, H.H., 1991. The Evolution of Control Architectures for Automated Manufacturing Systems. *Journal of Manufacturing Systems*, Vol. 10(1), pp.79-93.

Ding, C. & Wang, R., 2012. Thermal Contact Conductance of Stainless Steel-GFRP Interface under Vacuum Environment. *Experimental Thermal and Fluid Science*, Vol. 42(1), pp.1-5.

Dobie, G., Summan, R., Gareth Pierce, S., Galbraith, W. & Hayward, G., 2011. A Noncontact Ultrasonic Platform for Structural Inspection. *IEEE Sensors Journal*, Vol. 11(10), pp.2458-468.

Dowty, M.B. & Yurchenco, J.R., 2006. *Passenger Seat with Tilting Seat Bottom*. [Online] Available at: http://www.google.com/patents/US7063386 [Accessed 24 September 2014].

Duffie, N.A., Chiturri, R. & Mou, J., 1988. Fault-Tolerant Heterarchical Control of Heterogeneous Manufacturing System Entities. *Journal of Manufacturing Systems*, Vol. 7(4), pp.315-328.

Duffie, N.A. & Piper, R.S., 1987. Non-Hierarchical Control of a Flexible Manufacturing Cell. *Robotics and Computer-Integrated Manufacturing*, Vol. 3(2), pp.175-179.

EAS, 2014. *Quick Die Change Systems*. [Online] Available at: http://www.easchangesystems.com/uk/ [Accessed 31 October 2014].

Exitech, 2014. *Exitech E1-1325 CNC Planing Machine*. [Online] Available at: http://sh-cnc.en.alibaba.com/product/852406291-210194680/EXCITECH_E1_1325_Woodworking_cnc_planing_machine.html [Accessed 01 November 2014].

Expert Choice, 2014. *Expert Choice: For Collaborative Decision Making*. [Online] Available at: http://expertchoice.com/ [Accessed 30 September 2014].

FIPA-OS, 1999. *FIPA-OS*. [Online] Available at: http://fipa-os.sourceforge.net/index.htm [Accessed 20 September 2014].

Fletcher, M. & Deen, S.M., 2001. Fault-Tolerant Holonic Manufacturing Systems. *Concurrency and Computation: Practice and Experience*, Vol. 13(1), pp.43-70.

Forman, E.H. & Gass, S.I., 2001. The Analytical Hierarchy Process - An Exposition. *Operations Research*, Vol. 49(4), pp.469-486.

Forwell, 2014. *Quick Die Change System*. [Online] Available at: http://www.forwell.com/english/quick-die-change-system.htm [Accessed 31 October 2014].

Friedrich, K. & Hou, M., 1998. On Stamp Forming of Curved and Flexible Geometry Components from Continuous Glass Fiber/Polypropylene Composites. *Composites Part A*, Vol. 29(3), pp.217-226.

Friedrich, K., Hou, M. & Krebs, J., 1997. Thermoforming of Continuous Fibre/Thermoplastic Composite Sheets. D. Bhattacharyya, ed. *Composite Sheets Forming*. 1st ed. Elsevier. pp.91-160.

Groppe, D., 2003. Robotic layup of composite materials. *Assembly Automation*, Vol. 23(2), pp.153-158.

Grouve, W.J.B., Warnet, L.L., Rietman, B. & Akkerman, R., 2012. On the Weld Strength of In-situ Tape Placed Reinforcements on Weave Reinforced Structures. *Composites Part A*, Vol. 43(9), pp.1530-536.

Haase, W., Ungerer, D. & Mohr, F., 2014. Automated Non-Destructive Examination of Complex Shapes. In *11th European Conference on Non-Destructive Testing*. Prague, Czech Republic, 2014.

Haas, E., Schwarz, R.C. & Papazian, J.M., 2002. Design and Test of a Reconfigurable Forming Die. *Journal of Manufacturing Processes*, Vol. 4(1), pp.77-85.

Hall, K.H., Staron, R.J. & Vrba, P., 2005. Experience with Holonic and Agent-Based Control Systems and their Adoption in Industry. V. Marik, R.W. Brennan & M. Pechoucek, eds. *Holonic and Multi-Agent Systems for Manufacturing*. Berlin: Springer Berlin Heidelberg. pp.1-10.

Harker, P.T. & Vargas, L., 1987. The Theory of Ratio Scale Estimation: Saaty's Analytic Hierarchy Process. *Managment Sciences*, Vol. 33(11), pp.1383-403.

Harper, C.A., 2004. Composite Materials and Processes. *Handbook of Plastics, Elastomers, & Composites*. 4th ed. McGraw-Hill. pp.262-279.

Herrmann, S. & Purol, H., 2006. Fibre Reinforced Thermoplastics - Opportunities and Challenges for Large-Scale Production. B.E.N. Herald & F.N. Giovanni, eds. *CETEX. From Scratch to Flight*. Bremen, Germany. Ch. 3. pp.25-32.

Hou, M., 1996. Stamp Forming of Fabric-Reinforced Thermoplastic Composites. *Polymer Composites*, Vol. 17(4).

Hou, M., Ye, L., Lee, H. & Mai, Y., 1998. Manufacture of a Carbon Fabric-reinforced Polyetherimide (CF/PEI) Composite Material. *Composites Science and Technology*, Vol. 58(2), pp.181-190.

Howell, D., Lizotte, A.M. & Dequine, D.L., 2013. Design, Analysis, Manufacture, and Test of a Continuous Fiber Reinforced Thermoplastic Stringer with Local Reinforcements. *SAMPE*, pp.2748-763.

Hsu, D.K., 2008. Nondestructive Inspection of Composite Structures: Methods and Practice. In *Proceedings of the 17th World Conference on Nondestructive Testing*. Shanghai, China, 2008.

IAPD, 2010. Thermoplastic composites for aerospace. In *IAPD Magazine,* April/May.

Incropera, F., Dewitt, D., Bergman, T. & Lavine, A., 2007. *Fundamentals of Heat and Mass Transfer*. 6th ed. John Wiley & Sons.

Intelligent Manufacturing Systems, 1990. *Intelligent Manufacturing Systems*. [Online] Available at: http://www.ims.org/ [Accessed 20 September 2014].

Ji Seok, L., Seok Jin, H., Woong-Ryeol, Y. & Tae, J.K., 2007. The Effect of Blank Holder Force on the Stamp Forming Behavior of Non-Crimp Fabric with a Chain Stitch. *Composite Science and Technology*, Vol. 67, pp.357-366.

Joffe, A., Kaplan, D., Kaplinsky, R. & Lewis, D., 1995. Manufacturing Performance. *Improving Manufacturing Performance in South Africa*. 1st ed. Rondebosch: UCT Press (Pty) Ltd. pp.9-13.

JOpenShowVar, 2014. [Online] Available at: https://github.com/aauc-mechlab/jopenshowvar [Accessed 19 June 2014].

Kelkar, A., Nagi, R. & Bahattin, K., 2005. Geometric Algorithms for Rapidly Reconfigurable Mold Manufacturing of Free-form Objects. *Computer-Aided-Design*, Vol. 37(1), pp.1-16.

Kinetics, 2014. *Interchangeable Mold Inserts*. [Online] Available at: http://www.kinetics.com/mim-design-guide/interchangeable-mold-inserts/ [Accessed 31 October 2014].

Kleespies, H.S. & Crawford, R.H., 1998. Vacuum Forming of Compound Curved Surfaces with a Variable Geometry Mold. *Journal of Manufacturing Systems*, Vol. 17(5), pp.325-337.

Koc, B. & Thangaswamy, S., 2011. Design and Analysis of a Reconfigurable Discrete Pin Tooling System for Molding of Three-dimensional Free-form Objects. *Robotics and Computer-Integrated Manufacturing*, Vol. 27(2), pp.335-348.

Koestler, A., 1969. *The Ghost in the Machine*. London: Arkana Books.

Komanduri, R., 1997. Machining of Fibre-Reinforced Composites. *Machining Science and Technology*, Vol. 1(1), pp.113-152.

Kordi, M., Husing, M. & Corves, B., September 2007. Development of a Multifunctional Robot End-effector System for Automated Manufacture of Textile Preforms. In *2007 IEEE/ASME International Conference on Advanced Intelligent Mechatronics*., September 2007.

Koren, Y., Heisel, U., Jovane, F., Moriwaki, T., G., P., Ulsoy, G. & Van Brussel, H., 1999. Reconfigurable Manufacturing Systems. *CIRP Annals - Manufacturing Technology*, Vol. 48(2), pp.527-540.

Koren, Y. & Shpitalni, M., 2011. Design of Reconfigurable Manufacturing Systems. *Journal of Manufacturing Systems*, Vol. 29(4), pp.130-141.

Kruger, K. & Basson, A.H., 2013. Multi-agent Systems vs IEC 61499 for Holonic Resource Control in Reconfigurable Systems. *Procedia CIRP*, Vol. 7(1), pp.503-508.

KUKA, 2014. [Online] Available at: http://www.kuka-robotics.com/res/sps/a737ee03-5832-4c95-9d91-84e0de80c664_KUKA_PB_MITTLERE_TL_en.pdf [Accessed 05 November 2014].

KUKA, 2014. *Planning (KUKA Load)*. [Online] Available at: http://www.kuka-robotics.com/en/products/software/planning/ [Accessed 15 October 2014].

Lanco, 2014. [Online] Available at: http://www.lanco.net/static/Transportsystem.htm [Accessed 05 November 2014].

Leitao, P., 2009. Agent-Based Distributed Manufacturing Control: A Starte-of-the-art Survey. *Engineering Applications of Artificial Intelligence*, Vol. 22(7), pp.979–991.

Leitao, P., Colombo, A.W. & Restivo, F., 2003. An Approach to the Formal Specification of Holonic Control Systems. V. Mark, D. McFarlane & P. Valckenaers, eds. *Holonic and Multi-Agent Systems for Manufacturing*. Berlin: Springer-Verlag. pp.59-70.

Leitao, P. & Restivo, F., 2003. Towards Autonomy, Self-Organisation and Learning in Holonic Manufacturing. V. Marik, M. Pechoucek & J. Muller, eds. *Multi-Agent Systems and Applications III*. Berlin: Springer Berlin Heidelberg. pp.544-553.

Leitao, P. & Restivo, F., 2006. ADACOR: A Holonic Architecture for Agile and Adaptive Manufacturing Control. *Computers in Industry*, Vol. 57, pp.121-130.

Lim, T.C., Ramakrishna, S. & Shang, H.M., 1999. Axisymmetric Sheet Forming of Knitted Fabric Composite by Combined Stretch Forming and Deep Drawing. *Composites Part B*, Vol. 30, pp.495-502.

Lukaszewics, D.H., Ward, C. & Potter, K.D., 2012. The Engineering Aspects of Automated Prepreg Layup: History, Present and Future. *Composites*, Vol. 43(3), pp.997-1009.

MAAC Machinery Corporation, 2014. *Clampframes*. [Online] Available at: http://maacmachinery.com/products/detail/clampframes/ [Accessed 31 October 2014].

Machado, E.P., Gomes, L. & Chauvel, M., 2003. Marketing Engineering at Xerox Brazil: A Case Study. *Journal of Economics and Administration*, Vol. 2(2), pp.75-86.

Mallick, P.K., 2007. *Fiber-Reinforced Composites: Materials, Manufacturing, and Design*. 1st ed. London: CRC Press: Taylor and Francis Group.

Mallon, P.J. & Obradaigh, C.M., 2000. Compliant Mold Techniques for Thermoplastic Composites. A. Kelly & C. Zweben, eds. *Comprehensive Composite Materials*. Pergamon. Ch. 2.26. pp.873-913.

Marik, V. & Lazansky, J., 2007. Industrial Applications of Agent Technologies. *Control Engineering Practice*, Vol. 15, pp.1364-380.

McCool, R., Murphy, A., Wilson, R., Jiang, Z. & Price, M., 2011. Thermoforming of Continuous Fibre Reinforced Thermoplastic Composites. In *AIP Conference Proceedings*., 2011.

Mehrabi, M.G., Ulsoy, A.G. & Koren, Y., 2000. Reconfigurable Manufacturing Systems: Key to Future Manufacturing. *Journal of Intelligent Manufacturing*, Vol. 11(4), pp.403-419.

Milojicic, D., Breugst, M., Busse, I., Campbell, J., Covaci, S., Friedman, B., Kosaka, K., Lange, D., Ono, K., Oshima, M., Tham, C., Virdhagriswaran, S. & White, J., 1998. MASIF: The OMG mobile Agent System Interoperability Facility. *Personal Technologies*, Vol. 2(2), pp.117-129.

Mineo, C., Herbert, D., Morozov, M. & Pierce, S.G., 2012. *Robotic Non-Destructive Inspection*. [Online] Available at: http://www.bindt.org/downloads/NDT2012_4C2.pdf [Accessed 03 November 2014].

Mitchell, T.A., Chestney, J.A. & Sarhadi, M., 1994. A Prototype Assembly Cell for Lay-up of Carbon Composite Preforms. *Robotics & Computer-Integrated Manufacturing*, Vol. 11(4), pp.335-343.

Mokhtar, M., 1995. Thermoplastic Composites vs. Thermoset Composites. *Buletin FKKKSA*, Vol. 9(1), p.24.

Murtagh, A., 1997. Characterisation of Shearing and Frictional Behaviour During Sheet Forming. D. Bhattacharyya, ed. *Composite Sheet Forming*. Auckland, New Zealand : Elsevier. pp.163-216.

Negarestani, R., 2010. *Laser Cutting of Carbon Fibre-Reinforced Polymer Composite Materials*. PhD thesis. Manchester: School of Mechanical, Aerospace and Civil Engineering.

Non-Destructive Academy of South Africa, 2014. [Online] Available at: http://www.nondestructive.co.za/main.html [Accessed 03 November 2014].

North Sea Plastics, 2014. *Thermoplastic Convection Ovens*. [Online] Available at: http://northseaplastics.com/thermoplastic-ovens/ [Accessed 02 November 2014].

Nwana, H.S., Lee, L. & Jennings, N.R., 1996. Co-Ordination in Software Agent Systems. *BT Technology Journal*, Vol. 14(4), pp.79-88.

Olsen, H.B. & Craig, J.J., 1993. Automated Composite Tape Lay-Up Using Robotic Devices. In *IEEE International Conference on Robotics and Automation*. ATLANT, G.A., 1993.

Olympus, 2014. *Phased Array CFRP Inspection*. [Online] Available at: http://www.olympus-ims.com/en/omniscan-pa/flat-panels/ [Accessed 03 November 2014].

Patil, R.S., Fikes, R.E., Patel-Schneider, P.F., McKay, D., Finin, T., Gruber, T. & Neches, R., 1998. JAVA-Based Agent Platform Evaluation. In *Principles of Knowledge Representation and Reasoning: Proceedings of the Third International Conference.*, 1998. Morgan Kaufman.

Pereira, A., Botelho, E.C., Costa, M.L., Narita, N.E. & Tarpani, R., 2012. A Review of Welding Technologies for Thermoplastic Composites in Aerospace Applications. *Journal of Aerospace Technology and Management*, Vol. 4(3), pp.255-265.

Perry, M.J., 2012. *U.S. Chamber of Commerce Foundation*. [Online] (1.0) Available at: http://www.uschamberfoundation.org/ [Accessed 13 July 2013].

PreWired, 2014. *Thermoforming*. [Online] Available at: http://www.prewiredcontrols.com/thermoforming/ [Accessed 02 November 2014].

Robotmaster, 2014. [Online] Available at: http://www.robotmaster.com/ [Accessed 10 November 2014].

Roemheld, 2014. *Quick Die/Mould Change Products*. [Online] Available at: http://www.roemheld.co.uk/product_hilma_qdc.htm [Accessed 31 October 2014].

Royal TenCate, 2013. *TenCate Industrial Composites*. [Online] Available at: www.tencate.com/ [Accessed 12 October 2014].

Ruth, D.E. & Mulgaonkar, P., 1990. Robotic Lay-Up of Prepreg Composite Plies. In *IEEE International Conference on Robotics and Automation*. Cincinnati, OH, 1990.

Saaty, R.W., 1987. The Analytic Hierarchy Process—What it is and How it is Used. *Mathematical Modelling*, Vol. 9(3-5), pp.161-176.

Sarhadi, M., 1993. Automated Lay-up of Non-rigid Fabrics. In *IEE Manufacturing Technology Update*. London, 1993.

Schlimbach, J. & Mitschang, P., 2006. Process-Based Cycle Time Estimation for the Thermoplastic Tape Placement. *Journal of Thermoplastic Composite Materials*, Vol. 19(5), pp.507-529.

Schmalz, 2014. *Vacuum End Effectors*. [Online] Available at: http://us.schmalz.com/np/pg/produkte?hier=155-156-4388 [Accessed 06 November 2014].

Setchi, R. & Lagos, N., 2004. Reconfigurability and Reconfigurable Manufacturing Systems: State-Of-The-Art Review. *2nd IEEE International Conference on Industrial Informatics*, pp.529-535.

Shahtukh, A.I., Subramanian, S. & Allam, Y.S., 1999. Introduction to Cellular Manufacturing Systems. A.I. Shahtukh, ed. *Handbook of Cellular Manufacturing Systems*. 1st ed. John Wiley & Sons, Inc. p.2.

Shang, J., Sattar, T., Chen, S. & Bridge, B., 2007. Design of a Climbing Robot for Inspecting Aircraft Wings and Fuselage. *Industrial Robot: An International Journal*, Vol. 34(6), pp.495-502.

Shirinzadeh, B., Alici, G., Wei Foong, C. & Cassidy, G., 2004. Fabrication Process of Open Surfaces by Robotic Fibre Placement. *Robotics and Computer-Integrated Manufacturing*, Vol. 20, pp.17-28.

Shirinzadeh, B., Cassidy, G., Oetomo, D., Alici, G. & Ang Jr., M.H., 2007. Trajectory Generation for Open-Contoured Structures in Robotic Fibre Placement. *Robotics and Computer-Integrated Manufacturing*, Vol. 23, pp.380-394.

Shirinzadeh, B., Foong, C.W. & Tan, B.H., 2000. Robotic Fibre Placement Process Planning and Control. *Assembly Automation*, Vol. 20(4), pp.313-320.

Sirris Leuven-gent Composites Application Lab, 2014. *CO-Pers*. [Online] Available at: http://www.slc-lab.be/projects/co-pers/co-pers [Accessed 05 November 2014].

Smith, R.G., 1980. The Contract Net Protocol: High-level Communication and Control in a Distributed Problem Solver. *IEEE Transactions on Computers*, Vol. C-29(12), pp.1104-113.

Sorrentino, L., Carrino, L., Tersigni, L. & Leone, A., 2009. Innovative Tape Placement Robotic Cell: High Flexibility System to Manufacture Composite Structural Parts with Variable Thickness. *Journal of Manufacturing Science and Engineering*, Vol. 131(4).

Statistics South Africa, 2013. *Statistical Release: Gross Domestic Product*. Statistical Release. Pretoria: Statistics South Africa.

Teti, R., 2002. Machining of Composite Materials. *CIRP Annals - Manufacturing technology*, Vol. 51(2), pp.611-634.

TextileWeb, 2014. *M9000 Digital Cutting System*. [Online] Available at: http://www.textileweb.com/doc/m9000-digital-cutting-system-ets-m9000-0001 [Accessed 01 November 2014].

The Foundation for Intelligent Physical Agents, 1999. *The Foundation for Intelligent Physical Agents*. [Online] Available at: http://www.fipa.org/ [Accessed 20 September 2014].

The Foundation for Intelligent Physical Agents, 2002. *FIPA Specification*. [Online] IEEE Foundation for Intelligent Physical Agents Available at: http://www.fipa.org/ [Accessed 20 September 2014].

Throne, J.L., 1996. *Technology of Thermoforming*. 1st ed. New York: Hanser Publishers.

Tooling and Production, 2013. *New Composite Processing System Offers Head Docking, Switches from Fiber Placement to Tape Laying in Minutes*. [Online] Available at: http://www.toolingandproduction.com/cms/tap/opens/newsblast-view-tap.php?newsletter_idx=3&blast_hdr_idx=115 [Accessed 2013].

UNStats, 2013. *United Nations Statistics Division*. [Online] (1.0) Available at: http://unstats.un.org/unsd/snaama/dnllist.asp [Accessed 13 July 2013].

Vaidya, O. & Kumar, S., 2006. Analytic Hierarchy Process: An Overview of Applications. *European Journal of Operational Research*, Vol. 169(1), pp.1-29.

Van Brussel, H., Wyns, J., Valckenaers, P., Bongaerts, L. & Peeters, P., 1998. Reference Architecture for Holonic Manufacturing Systems: PROSA. *Computers in Industry*, Vol. 37, pp.255-274.

Vokrinek, J., Biba, J., Hodik, J., Vynihal, J. & Pechoucek, M., 2007. Competitive Contract Net Protocol. In *SOFSEM '07 Proceedings of the 33rd Conference on Current Trends in Theory and Practice of Computer Science*. Berlin, 2007. Springer.

Vrba, P., 2003. JAVA-Based Agent Platform Evaluation. V. Marik, D. McFarlane & P. Valckenaers, eds. *Holonic and Multi-Agent Systems for Manufacturing*. Berlin, Germany: Springer. pp.47-58.

Wakeman, M.D., Bonjour, F., Bourban, P.E., P., B., Juillerat, F. & Manson, J.A.E., 2009. Robotic Tow Placement for Local Reinforcement of Glass Mat Thermoplastics. *Composites*, Vol. 33(9), pp.1199–208.

Walczyk, D.F., Lakshmikanthan, J. & Kirk, D.R., 1998. Development of a Reconfigurable Tool for Forming Aircraft Body Panels. *Journal of Manufacturing Systems*, Vol. 17(4), pp.287-296.

Watlow, 1997. *Radiant Heating with Infrared*. [Online] Watlow Available at: http://www.watlow.com/downloads/en/training/STL-RADM-89.pdf [Accessed 10 September 2014].

Wilks, C.E., 2000. *Processing Technologies for Woven Glass/Polypropylene Composites*. PhD Thesis. Notingham: University of Notingham.

Wooldridge, M. & Jennings, N.R., 1995. Intelligent Agents: Theory and Practice. *Knowledge Engineering Review*, Vol. 10, pp.115-152.

Xinology, 2014. *Bending and Tempering*. [Online] Available at: http://xinology.com:888/Glass-Processing-Equipments-Supplies-Consumables/glass-tempering/glass-tempering-furnace/feature/bending-tempering.html [Accessed 16 October 2014].

Yeung, H. & Kamineni, R., 2007. A Study on the Application of Advanced Thermoplastic Composites for Use in Building Construction Industry. In *Asia-pacific Conference on FRP in*

Structures. Hong Kong, 2007. Dept. of Civil Engineering, University of Hong Kong , Hong Kong.

Zhang, Z. & Sarhadi, M., 1996. An integrated CAD/CAM System for Automated Composite Manufacture. *Journal of Materials Processing Technology*, Vol. 61, pp.104-109.

Zoghi, M., ed., 2014. *The International Handbook of FRP Composites in Civil Engineering.* Broken Sound Parkway: Taylor & Francis Group.