Framework to Develop and Evaluate Process Chains for Resource Efficiency

M.K. Oettel[1], H. van der Schyff[2], M.B. Bezuidenhout[2], G.A. Oosthuizen[2]
[1]Department of Mechanical Engineering, HTW-Dresden
[2]RPD Labs, Department of Industrial Engineering, University of Stellenbosch

Abstract

Continuous development of new, and the improvement of existing products yields a vast collection of concepts and prototypes. Such products do not yet necessarily have established process chains. An area therefore exists for the development of novel manufacturing process chains towards the production of such products. In order to select a process chain most suited to the user's needs, it should be evaluated with regards to the design space in which it is applied. This paper presents a framework to create and evaluate resource efficient process chains, with an application example in the context of integrated medical implants. To realize this aim, a guideline was developed to lead the user through the entire thinking process for process chain evaluation. An empty template provides the user with creative freedom to apply the included methods for idea generation. After creating process chain variations, an assessment of each is executed. An evaluation score ranks the process chains in order of suitability for its specific purpose.

Keywords

Process Chain; Framework; Process Chain Evaluation

1 INTRODUCTION

The creation of process chains is an important part of product development. The process chain directly influences the costs of the product along with the production time and other associated parameters. It also defines which and how much resources are necessary to produce the product [1]. The resources relate to all fields of the company, for example manpower, material or capital investments (business resources). In execution of the software however, resources are specific to user defined scales, be it industrial, small to medium, artisan, or private. Importance for efficient use of resources is evident from rising costs in all business sectors [2-4]. It therefore also requires focusing on resource efficiency when a new process chain is developed [4]. To improve a process chain's resource efficiency, new manufacturing technologies can be utilised. For example, with additive manufacturing (AM), the user is able to significantly reduce the material waste compared to conventional methods. Another advantage is the high geometrical freedom that allows for adding functionality to existing products [5]. Certain studies suggested enhancements for medical hip implants such as drug delivery channels to reduce infections and sensors to detect the loosening of an implant [6-8]. Therfore an application model is based on studies from Bezuidenhout *et. al.* [8, 9] who demonstrated a sustained antibiotic release profile from conceptual drug delivery features produced with AM for eventual incorporation into cementless hip stems. Most of these technologies, however, are not yet fully integrated into a process chain, because it is difficult to evaluate the process chains with new technologies to determine whether one process chain is more efficient than another [10]. Blanch et al. [11] and Mousavi et al. [3] described different approaches to evaluate or improve process chains, but these approaches are focused on specific fields, for example, mechanical parts or only energy consumption. Such approaches are not necessarily user friendly for any client. Therefore this paper proposes a generic guideline, along with a software program, for the evaluation of process chains with an approach that is centred on the user defined importance for each factor within the process chain under consideration. The software can also be implemented theoretically in a learning / teaching environment to elucidate inherent differences between manufacturing processes and why certain operations are better suited to specific process chains than others.

2 FRAMEWORK AND METHODOLOGY

The architecture of the framework is illustrated in Figure 1 which also graphically describes the methodology. The framework includes a guideline, represented by Figure 1 level A, to create process chains, and important indicators to serve as input parameters for the second part of the framework, the VBA (visual basic for application) Program represented by Figure 1 level B. Level C represents the final process chain which is the most resource efficient process chain for the customer's needs. In the first section of the Guideline the user has to specify the focus which to design for, *People*, *Planet* or *Profit*. The *Business Focus* considers social aspects along with environmental aspects and profit. The next step is to set the *Focus Areas* and

Requirements downstream below the *Business Focus*, shown in Figure 2. The different levels shown in Figure 2 (vertical light blue bars) represent the more detailed execution of the description order. In the most cases, not all requirements have the same importance to each user. For this purpose, all requirements receive a weighting during the application of the guideline. The weighting is created by using utility analysis. The batch size of production is a very important parameter when creating a new process chain for products, because it is the main indicator of production scale. If the user wants to produce large batches of a product, it is more important to have a short manufacturing time. With the tool the user can also consider that fact by creating the requirement production time and assigning a high weighting to it. The levels are then divided into sections based on the upstream dependency. The sections are represented by orange boxes in Figure 2. In these sections the user can subdivide a total of 100% according to the importance of each identified constituent in the section. The value for each constituent depends on its perceived impact on the process chain. The weighting for each requirement is obtained by multiplying the percentages left to right along each single path from business focus to requirement. In the second section of the guideline, the process chains are created (Figure 1 level A). It starts with the design of the part (Figure 1 No. 1), from that the manufacturing steps (MS) are derived and manufacturing methods (MM) are identified to realise these steps (Figure 1 No. 2). To gather all possible ways to realise the MS, the user should consider the question:

Which processes are able to execute the MS?

The next step in the guideline is the selection of material or a material combination for the product (Figure 1 No. 3). A brief literature survey is advised to find the proper material for your product, because new materials or alloys are continuously being invented and improved by certain companies and institutes [12, 13]. The user then has to ensure

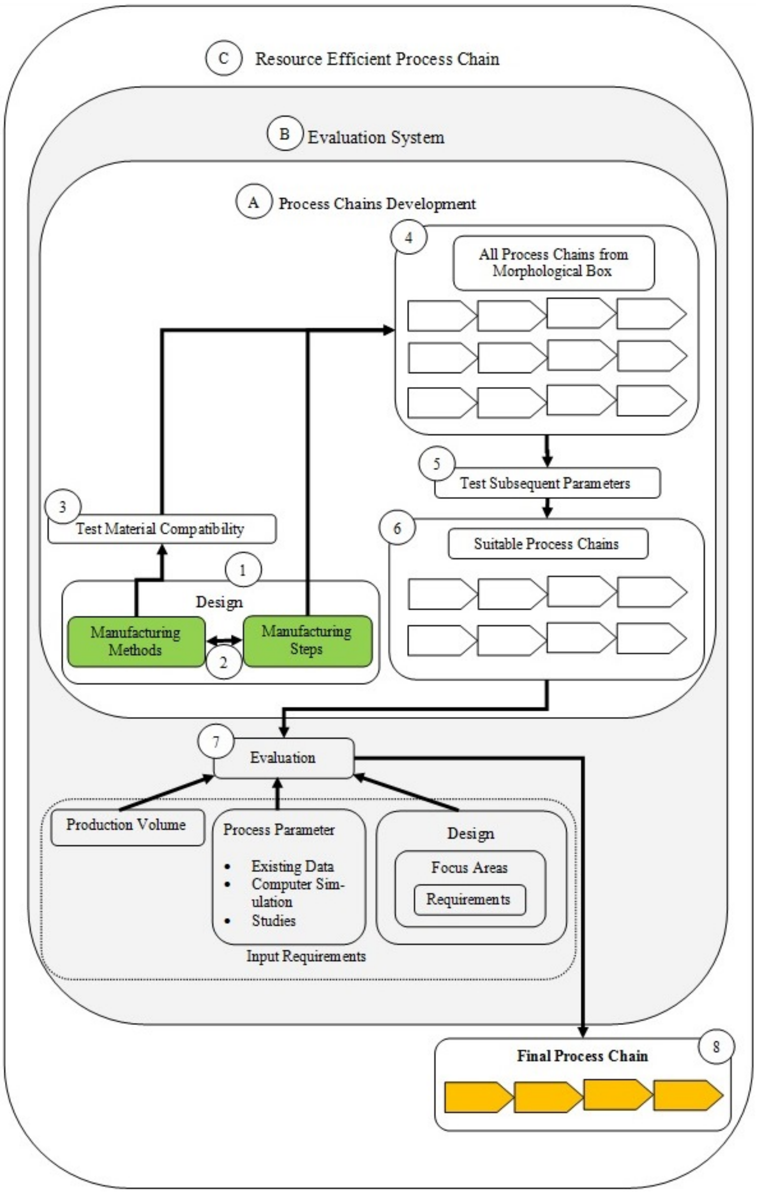

Figure 1 - Process steps to develop and evaluate resource efficient process chains

that each identified manufacturing method is compatible with the respective material. Lovatt et al. [14] termed it Processability and defines it as follows:

“The process must be able to modify, form or join the material in the required manner repeatably and reliably.” [14, p. 218]

Based on experience, reports or data sheets, the user has to decide if the identified process is indeed capable to work the specified material. If it is not, it has to be deleted (Figure 1 No. 3). At this stage the design process should be in an embodied or detailed point. The reason is, when the product has many design changes during the whole process, the user can obtain misleading results. In the following section a morphological box is used to create different process chains, Ritchey [15] defines the morphological analysis as follows:

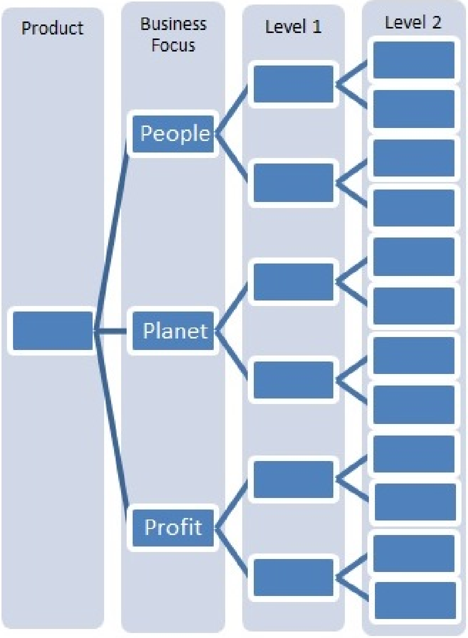

Figure 2 - Evaluation Hierarchy

“[…], general morphological analysis is a method for identifying and investigating the total set of possible relationships or “configurations” contained in a given problem complex.” [15, p. 3]

For this purpose, a set of parameters is prepared. A range of relevant conditions is assigned for each parameter to find all the possible paths from top to bottom. The morphological box is then prepared for process chain development (Figure 1 No. 4).

The manufacturing steps that the user derived in Figure 1 No. 2 are the base of the morphological box, and each is entered into the first column. The remaining MM from No. 3 will fill the row behind the corresponding MS. When all possible methods are gathered, the MM are connected top to bottom to create the process chains (Figure 1 No. 4). This step yields a selection of process chains for evaluation, but it also can include unfeasible process chains. These unrealistic process chains are due to the sequence of processes, because some processes are not able to run in front or behind another one. For example, it is not possible to mill a section and use sandcasting as a downstream process. Process chains with these errors have to be corrected (Figure 1 No. 5). When the procedure is finished, only feasible chains remain (Figure 1 No. 6). These process chains need to be assessed with the program (Figure 1 level B). For reliable results, it is necessary to have detailed information about all the encompassed processes. For this purpose the user has to gather information in different ways. Data bases, computer simulations of the processes, and experience with the technology, or case studies can provide information. If all required information is collected, the program should be utilized at the next step (Figure 1 No. 7).

The program comprises UserForms with insert fields, buttons, charts and a flip down chart. It also provides assisting texts while working with it. The program is based on VBA coding as mentioned above and can work with up to 10 process chains and up to 20 requirements. After opening the program, the first UserForm provide insert fields for all requirements with units and the accompanying weighting created with the guideline.

The second UserForm aids the operator to insert all process chains. Execution of the code is performed by clicking the button “*Add new Process Chain*”, which inserts the first process chain. After that, the customer has to write down the first name of the process and confirm the name by clicking “*Add process*”. After confirmation, the field will be empty again and ready for a new process name. The user has to write down all of the processes for the first chain. When he has finished the first chain, he can go on and click again “*Add new Process Chain*” and repeat the steps. When all process chains are embedded in the program, the button “*Insert Data*” continues the program.

The UserForm “*Data gathering*” provides an insert box to enter all collected data for the process chains. It starts with the first process chain and the first process in this chain and also with the first requirement that the user entered on UserForm1. After pressing the *“Insert”* button, the program continues and moves along each row and each requirement. When all fields have received a value, the input box instructs the user to click “*Continue*”.

The next UserForm shows the rating range used by the program for the evaluation process. With this Information the consumer can go on to the “*References and Goals*”. In this UserForm the customer has to determine the minimum and the maximum limits of the evaluation range for each requirement. The user can decide to create own goals / limits or use an existing process chain as a reference and derive the limits, but the user has to ensure that the total amounts of each requirement is between those limits. The range is inserted by selecting the requirement from the drop down box and entering the minimum and the maximum values. The data is confirmed by clicking "*Save References and Goals*" to pass it to the program. This procedure has to be repeated until the last requirement has received its limits.

To finish the UserForm, the customer can continue to "*Show Results*" and a PDF sheet is created, level C in Figure 1. The Sheet contains the different scores for the process chains from the evaluation process. A bar-chart on the bottom of the sheet compares the scores from the process chains. With the PDF sheet, the customer can easily decide which process chain he should choose depending on these specific needs (Figure 1 No. 8).

3 APPLICATION OF THE FRAMEWORK

To demonstrate the functionality of the prototype evaluation program, a conceptual device without an established process chain has been identified in the form of a cementless hip replacement femoral stem with drug delivery features. Promising results have been obtained when conceptual features were evaluated [9]. A conceptual femoral stem encompassing such features is presented in Figure 3.

Figure 3 - Application model

Utilising techniques discussed for Level A in Figure 1, a variety of four processes have been identified based on the design and manufacturing requirements as defined in Zhang *et al.* [16]. Different possible manufacturing techniques were considered using the process models from Hermann and Thiede [4]. An example for these process chains is presented in Figure 4. It is important to note that this application case serve as a demonstration platform for the prototype software and is not claimed to yield an optimal process chain for the actual manufacture of such a device, as much more detail regarding specific product attributes would be required.

According to the criteria set in Figure 1, No. 2, the MM should be developed with appropriate MS. Alternative process chains have been developed with different MS dependent on the properties of the raw material. These are:

1) Milling on 2 separate billets on a 5-axes CNC milling machine, where the outer shape of the implant is roughed from both billets, followed by finishing. Once these two parts have been machined, they can be combined using a press fit between the holes on the one piece, and the pegs on the other piece.
2) A hybrid process chain using milling and SLM where the implant is divided into a top- and bottom section. The top section contains no complexities, which allows for easy machining. The bottom piece will be manufactured using the SLM process. All of the drug delivery channels are inside of the bottom piece.
3) The third process chain is using the SLM process to manufacture the entire implant, with emphasis on appropriate processing parameters.
4) For the fourth chain, a wire cutting and milling process are described. Two billets will again be used, but instead of using milling for the rough outer shape, wire cutting will be used on both billets. Finishing is performed on the milling machine.

The next step is to evaluate these chains according to user defined specifications in the evaluation hierarchy as per Figure 2. For this evaluation, the defined specifications are, Cost [South African Rand], manufacturing time [minutes] and material waste [kg]. If a part is to be manufactured for the purpose of making a profit, then the production costs are important. As soon as multiple parts are required before a given deadline, then the manufacturing time as well as the cost per part is of high importance. Titanium is an expensive material to purchase, and therefore a need exist to reduce the material waste for each step of the process. In

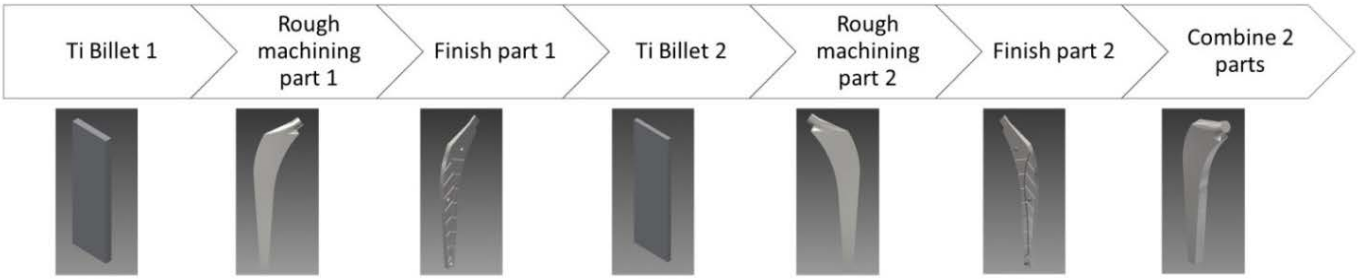

Figure 4 - Process Chain 1, milling on two separate billets

this case, the waste is defined as the loss of material during the manufacturing process in each MS. Furthermore, revenue from selling to recycling companies and ecological relief from use of recycled materials are not included in the scope. Specifications regarding the geometry, surface integrity and mechanical specifications should also be considered. However, such details considering the process chain in terms of manufacturing and also for intended use are outside the scope and purpose of this study. Furthermore, based on the needs of the user, details regarding evaluation criteria are bound to vary for different applications. To allow for user variability with regards to the identified focus areas in this paper, they were each evaluated at two levels, low and high. Since there are three focus areas, and weightings are required to total a hundred percent, the remaining two factors in the ratio has further been divided into two levels as well, yielding four combinations per factor. This is presented in Table 1.

Each MS involved in each process chain was entered into the program. For each process a value is required for the cost involved, the time of the process as well as the material waste, which was calculated as input material mass – output material mass. In order to evaluate the process chains against each other, the program requires upper and lower limits regarding each criterion.

	Low (Independent Static Variable)				**High (Independent Static Variable)**			
	#	C	T	W	#	C	T	W
Cost C [%]	**1**	20	26.6	53.4	**3**	60	13.3	26.7
	2	20	53.4	26.6	**4**	60	26.7	13.3
Time T [%]	**5**	26.6	20	53.4	**7**	13.3	60	26.7
	6	53.4	20	26.6	**8**	26.7	60	13.3
Waste W [%]	**9**	26.6	53.4	20	**11**	13.3	26.7	60
	10	53.4	26.6	20	**12**	26.7	13.3	60

Table 1 - Weighting set up for the simulation runs

This has been selected as the best and worst value for each criterion. For example, the best manufacturing time (for the entire process chain) will be the upper limit, and the worst time would be the lower limit. Each MS involved in each process chain was entered into the program.

Input values are based on current industry costs associated with each process, simulated manufacturing time and calculated material waste. A breakdown of the costs involved shows the hourly rate of each process, extra labour costs, tooling cost, programming cost, and material costs. The time factor is determined by calculating the time to complete each step in the process chain, and summing the time across the entire process chain.

For the evaluation it was assumed that one machine is available for a process step, and that no processes can be completed simultaneously. Material waste is defined as the difference in mass between starting material and final part design. Using the density of titanium, and volume information from the CAD software, the mass difference could be calculated. For the SLM processes, the mass of the support structure that is built by the SLM machine is the material waste for the process. The UserForm of the program requires input data for each process step of every process, for all defined evaluation criteria. The program was then executed for each of these combinations with the results summarised in Table 2. The stars behind the requirements in Table 2 imply that the requirement was an independent static variable at low or high specification. For each execution a graphical representation is printed to the user, an example is presented in Figure 5.

From Table 2, the CNC process chain (process chain 1) dominates especially when cost is of high importance and waste low. As expected, a process chain incorporating SLM becomes the best when waste becomes highly important. From this theoretical evaluation it is therefore evident that the program also reveals interactions between factors and their influence on the suggested process chain. For further evaluations of the program, more realistic manufacturing times should be utilised to allow for concurrent processes.

Setup Ratio #	**Best Process chain**	**Low**	**High**
1	Hybrid CNC-SLM	C*	W
2	CNC	C*	T
3	CNC	T	C*
4	CNC	W	C*
5	Hybrid CNC-SLM	T*	W
6	CNC	T*	C
7	CNC	C	T*
8	CNC	W	T*
9	CNC	W*	T
10	CNC	W*	C
11	Hybrid CNC-SLM	C	W*
12	Hybrid CNC-SLM	T	W*

Table 2 - Best process chain for different simulation runs in evaluation software

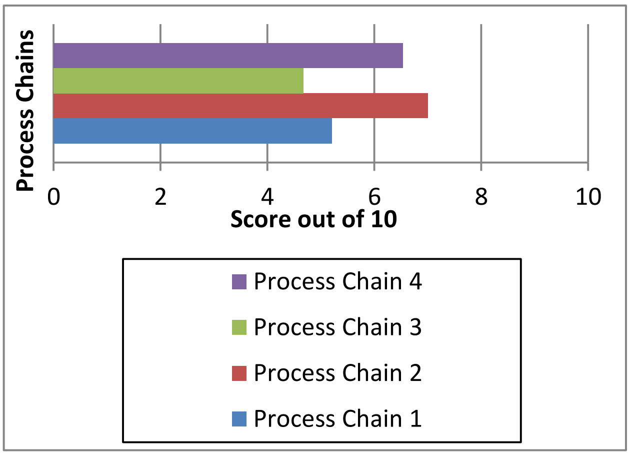

Figure 5 - Typical output for evaluated process chains from simulated weighting percentages

4 CONCLUSION

This prototype program proves to possibly be a helpful tool in evaluating process chains for a predefined set of specifications. If more detail is used within the set of criteria, a wider spectrum can be used to evaluate process chains. Therefore any criteria (if the input data is available) can be added, and the process chain can be evaluated accordingly. A benefit of this program is the fact that the evaluation of the process chain is done by evaluating each step separately. Therefore individual steps can be identified in order to specify where improvements can be implemented.

5 FURTHER WORK

At this point the *Guideline* and the *program* are not validated with an industry case study. Further work should therefore be to validate the program with examples from industry and eliminate bugs in the coding. The program can also be adapted to iteratively aid in improving processes with *Plan do Check Act* for obtaining more precise evaluations of a factory's production processes.

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7 BIOGRAPHY

Markus Oettel is currently studying mechanical engineering towards a graduate Diploma at the HTW Dresden in Germany

Herman van der Schyff holds a Bachelor degree in Industrial Engineering from the university of Stellenbosch, South Africa.

Martin Bezuidenhout is currently studying towards a PhD in Industrial Engineering at Stellenbosch University.

Gert Adriaan Oosthuizen obtained his PhD degree from Stellenbosch University. In 2011 he became a CIRP research affiliate and senior lecturer. In 2014 he became head of Rapid Product Development Laboratory at Stellenbosch University.