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# DEVELOPMENT OF A FRAMEWORK FOR IMPROVING ENGINEERING PROCESSES

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## ABSTRACT
The complexity of designing products such as gas turbine components leads to enormous difficulties in understanding where the main design process inefficiencies are. It is extremely difficult to decide which improvements will have the most significant impact for a company or for a specific project. Another common issue found in the Aerospace industry is a consequence of basing a new gas turbine design on a previous concept which means that people generally don't question the overall design process. These issues, alongside a company's matrix organization, create difficulties in managing and improving the design processes. In order to overcome the mentioned problems, a framework has been developed and used in Rolls-Royce, aiming to assess and improve, in a systematic way, complex product development processes at component or system level. The framework involves the use of Value Stream Mapping (VSM) analysis to identify sources of waste in the design process, the use of Design Structure Matrix (DSM) to manage design iterations and complex interfaces, and process simulation to deal with its stochastic behavior and estimate and assess the benefit of potential developments.

*Keywords: Process improvement, Value Stream Map, Design Structure Matrix, Process Simulation, Lean Waste*

## 2 INTRODUCTION
The complexity of designing products such as gas turbine components leads to enormous difficulties in understanding where the main inefficiencies are in the design processes. Therefore it is extremely difficult to decide which improvements will have the most significant impact for a company or for a specific project. Another common issue found in the Aerospace industry is that the practice of basing a new gas turbine design on a previous concept generally means that people don't question the design processes, methods or tools in use. All of this associated with the matrix constitution commonly used in aerospace companies contributes to a difficulty in managing and improving the interfaces and dependencies between activities. On the other hand, the development of aerospace products such as gas turbine components is extremely complex and requires the best team performance. Quoting [1], the design of a jet engine is invariably a compromise of conflicting requirements, so what is the most efficient way of managing these conflicts to achieve a team best performance? Complex product development is also characterized by a significant amount of uncertainty.
Uncertainty in customer requirements and input data leads to an uncertain number of design iterations along with the specification's evolution. There is guidance on literature about leading with design uncertainty [2], design iterations [3] and communication within the design team [4]. There are, in literature and commercially, several tools to improve complex product development based on Gantt charts, PERT analysis, Design Structure Matrix (DSM), etc. However it is very difficult to capture all the relevant information to manage complex product development in an effective way using only one of these tools [5]. To overcome this problem, a framework is being developed to improve complex product development focusing on waste reduction (VSM), iteration management (DSM) and process map simulation. The combination and organisation of these tools results in a systematic process improvement framework.
The VSM method emerged as one of the main tools of Lean Manufacturing. VSM was originally used in an operations environment, where it was used as a graphical representation of the materials and information flow and as an analysis tool for identifying waste in manufacturing processes [6]. Waste was defined as any activity that consumes resources and is not valuable from the customer point of

view, in other words the customer wouldn't pay for it. Nowadays the Lean philosophy has been successfully extended to other areas outside of the manufacturing environment. The application of lean principles at an enterprise level can be found in the literature [7]. Even if the application of lean principles is already significantly explored in literature [8, 9], there is a lack of real examples and best practices. Consequently, there is a need for guidance on applying these tools for complex environments such as product development. McManus [9] developed a manual for using VSM in improving product development processes; however this manual is only applicable at component level and doesn't present any complex product development examples. One of the main challenges of applying VSM to engineering processes is the data collection and the definition of value and Lean waste in product development.

The use of DSM allows representing and manipulating complex processes in a graphical way, enabling an understanding of how tasks and information flows affect other groups of tasks and highlighting the iterative characteristic of the complex product development [10]. McManus [9] and Millard [8] recommended using the DSM to support the VSM analysis of complex and iterative design processes, but there are no examples of the benefit of using these two tools together. There is no framework or standard process of using VSM and DSM to improve product development including the benefit impact on the overall process.

Chalupnik et al. [2] showed the benefits of using simulation, to improve design processes but didn't address problems such as waste sources, communication problems or iterations complexity.

From the literature review, it was concluded that there is no tool or process framework which simultaneously addresses waste elimination, iteration control and simulating improvement scenarios (uncertainty and DOE).

The research was mainly divided in two case studies that supported the framework development in distinct ways: the first case study was fundamental to developing the framework at a component level and specifically focused on detailed engineering design and the second case study was essential for validation and to extend the framework to a system level application and to the prelim engineering design activities.

The paper is organized as follows. Section 2 presents the relevant literature review, focused on complex product development, Value Stream Map development for design applications, Design Structure Matrix and simulation of design processes. The framework structure and detailed steps are presented in Section 3. Section 4 describes the highlights from the case studies and Section 5 concludes and describes the next steps for this research.

## 3 ENGINEERING PROCESSES IMPROVEMENT FRAMEWORK

The complexity of gas turbine components, their development process and the company matrix organization make it extremely difficult to understand where the main problems of a design process are, who is struggling to meet the design criteria or where the space for improvement is in a specific design process. There are specialists for each area, this study identified the opportunity to improve the integration between teams. When a design problem is identified, improvement actions are launched at a local level. Since these actions are not managed at higher level, frequently some redundant actions are executed. Another point is that these actions are launched to solve a problem, for example to develop a new tool or method, but don't challenge the design process itself. Recently undertaken socio-technical research concluded that the focus has historically been in developing products, but modern tools and methodology will now allow for process development.

The proposed framework has been developed to challenge the current processes, identify where the inefficient activities are, where the interface problems within different teams are and to identify the benefit of solution development compared with the development effort. Figure 1 represents the framework structure.

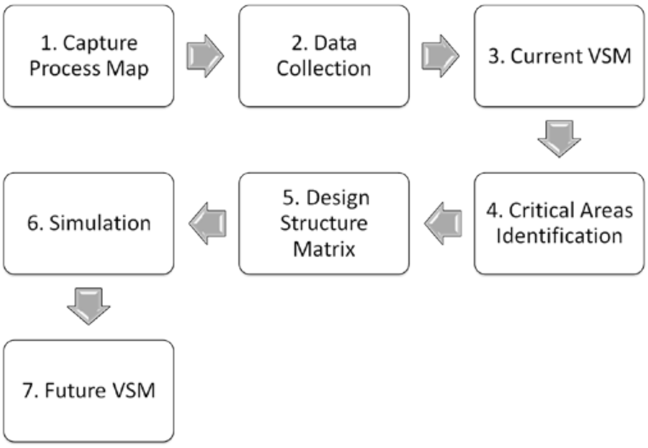



*Figure 1. Engineering Process Improvement Framework*

### 3.1 Capture Process Map

The main objectives of this first phase of the framework are to capture the activities sequence and to identify the key stakeholders in the process (internal/ external suppliers and customers). This information can be obtained by running workshops involving the experts of the main functional areas working on the design process under improvement.

In order to get the most benefit of these workshops, a preparation phase should include analyzing other project information such as Gantt charts or existing process maps.

On the workshop sessions, the function experts are invited to describe their activities, crucial input and outputs. In order to represent the process in a flexible way, leaving the process changeable during the discussions, the process is captured visually using post-it notes. This proved to be the most effective way to run the workshop sessions considering not only the process flexibility but also the stakeholders' engagement.

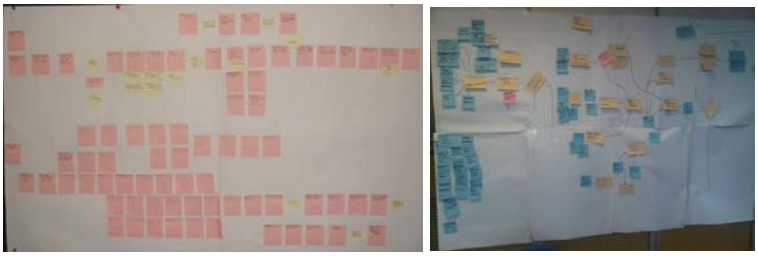


*Figure 2. Process Maps captured on Workshops Sessions*

The first concern during the session is capturing the sequence of activities, followed by capturing the links between the activities. These interactions between activities may be really complex and require the use of the Design Structure Matrix for a better visualization and understanding of the dependencies between activities.

The process map capture should be concluded only when all the function experts have described their activities and more than one session might be needed. However, this description doesn't need to be exhaustive because the process will be detailed further during the individual sessions of the Data Collection phase.

### 3.2 Data Collection

The aim of this phase is collecting the Value Stream Map data (time data and waste description) and simultaneously completing the process map. During the data collection phase, it is usual to identify missing activities and additional dependencies.

In order to go deeper into the details of each activity and for a better management of the specialists' time, the activity data collection should be done in structured individual interviews. To conduct these interviews, a data collection form was adapted from Millard work [8]. As with Millard's form, this data collection form captures the activity general information, the time metrics, inputs and outputs details, lean waste and other comments. The main difference between the two forms is related to time

data and resulted from the difficulty of collecting time data for design activities. From these first experiments, it was felt that the idea of collecting a time interval instead of a deterministic time value for the duration of each activity would work well. The collection form now includes not only the mode value, but also the minimum and maximum time values, this gives stochastic time information for each activity. Two benefits arise from this change: adding the stochastic information makes the interviewee's answer easier and simultaneously gives data for statistic analysis. This statistic analysis allows understanding of where the main sources of variation are in the process and where the improvement should be focused to assure the process is under control. Capturing the time needed to repeat an activity in case of iteration and differentiating between engineering and computing time are other major improvements in this adapted form. Engineering time is defined in this research as the time spent by the human resources and computing time, as the name suggests, the IT resources time.
The time metrics captured are similar to the metrics used by Millard [8] and McManus [9]: the elapsed time, the processing time and the core time. The elapsed time (ET) is defined as the time from authorization until completion of an activity. During this research it was considered that this metric is only useful when analyzing a process with dedicated resources. A longer elapsed time is expected if a company uses shared resources, either human or IT. However most of the time, the resource allocation is done according to the company strategy and cannot be easily changed based on one process analysis, even if from that process point of view the time spent on other projects is always considered to be waste. The core time (CT) is defined as the time spent on value-added activities which mean the customer would pay for those activities, while the processing time (PT) is the core time plus the time needed to prepare the activity, such as data and information retrieval or setup time.

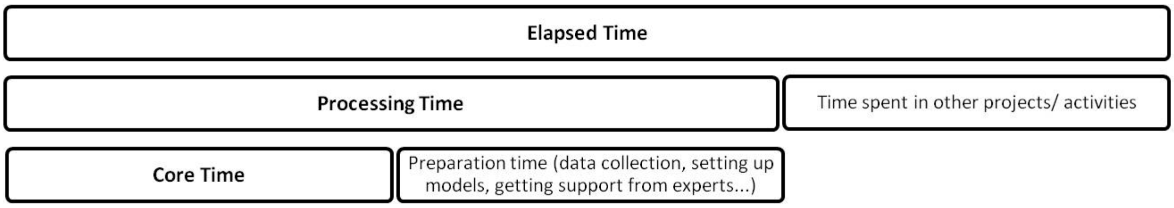



*Figure 3. Time metrics*

The lean-waste capture is also really important when analyzing the process improvement and discussing the potential improvement solutions. Originally seven types of lean waste were defined for manufacturing environments [6]. Morgan and Liker [4] redefined these waste types for engineering environments and on this research an extra waste type was added, the people waste (see definition on Table 1).
Table 1 presents the lean types of waste definitions and examples found from this research for each type of waste. For simplicity only one example for each waste type is presented.

*Table 1. 8 types of Lean waste redefined for engineering*

| **Lean Waste** | **Definition**[1] | **Example**[2] |
|---|---|---|
| Transportation | Moving information from place to place. | Copying and pasting the same information into many different places. |
| Inventory | Information that is not being used. | Due to department policy, information ready to be passed waiting for completion of a batch of activities causing 1 week delay. |
| Motion | Excess motion or activity during task execution. | Excess of meetings to present the same subject. |
| People[3] | Under or over using human resources capability. | The team leader doing stress activities to overcome the lack of human resources, instead of managing the team. |
| Waiting | Resources that are not being used; waiting for information or decisions. | Waiting for information needed; lack of required inputs to start an activity. |
| Over-production | Producing more or earlier than the next process needs. | Starting analysis with obsolete information, knowing that the activity will have to be repeated with up to date data. Finishing a design cycle when the inputs are already out |

| | | |
|---|---|---|
| | | of date. |
| Over-processing | Doing unnecessary processing on an activity or an unnecessary activity. | Repeating activities done in a different team due to lack of trust on the results. |
| Defects | Inspection to catch quality problems or fixing an error already made. | Repetition of an activity done with out of date data. |

[1] Definitions adapted from Morgan and Liker [4]
[2] Examples faced on the current research
[3] People waste is not defined in [4] but it was identified during this research.

Even if these interviews are planned to be structured, there is some time planned in the last part of the meeting for open comments that have not been addressed during the interview.
This data collection form proved to be effective when collecting Value Stream Map data and it is now being embedded in the Rolls-Royce VSM best practice for engineering improvement.

## 3.3 Current Value Stream Mapping (VSM)

The information captured in the previous phases allows, at this point, development of the complete VSM as a visual map with quantitative data. In contrast to the process map, the VSM loses the process details in terms of inputs and outputs, but on the other hand focuses on identifying value added and waste in the process. To facilitate this analysis the standard VSM notation was slightly adapted. McManus' VSM Manual [3] for product development was again essential during the development of this step. Each activity is represented by a rectangular box, as shown in Figure 4, which includes the function responsible for the activity (for example Aerodynamics), the activity name, the resources needed (human and computational) and finally the time metrics. Depending on the aim of the VSM the time metrics can be more or less detailed, for example if it is a communication map the short version is shown. For a complete analysis a detailed representation is recommended, including the separation between engineering time and computational time (Figure 5) and the time taken for iterations in case the activities are done more than once (Figure 6). For analysis purposes, the activity's efficiency can also be included in the VSM which can be supported by a color code, representing with green all the activities in which the efficiency is high, yellow for acceptable efficiencies and red for inefficient activities. The activity efficiency is defined as the ratio between Processing Time and the Core Time. The acceptable efficiency values should be defined considering the current/ expected (target) efficiencies of the process under improvement.

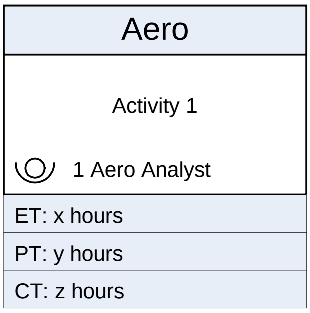



*Figure 4. Activity representation in the VSM*

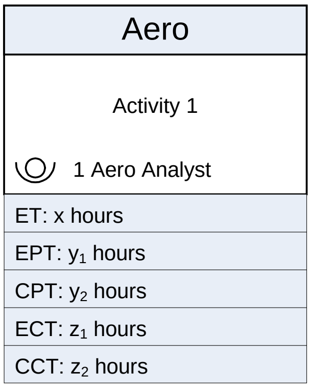



*Figure 5. Activity representation in the VSM differentiating between Engineering (EPT, ECT) and Computational (CPT, CCT) time*

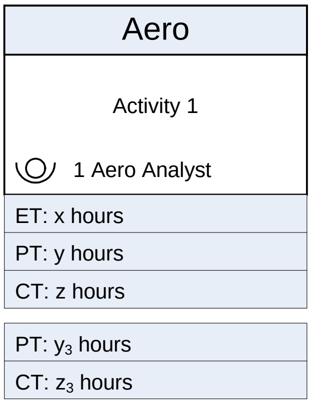



*Figure 6. Activity representation in the VSM including iteration data*

The activities are represented in the sequence in which they are performed, in parallel if this is the case which sometimes brings a lot of complexity to the VSM and makes it much easier to understand when viewed with the respective DSM (please see Section 2.5).
For purpose of demonstration, Figure 7 shows a VSM example. The symbols presented on the map are described in Table 2.

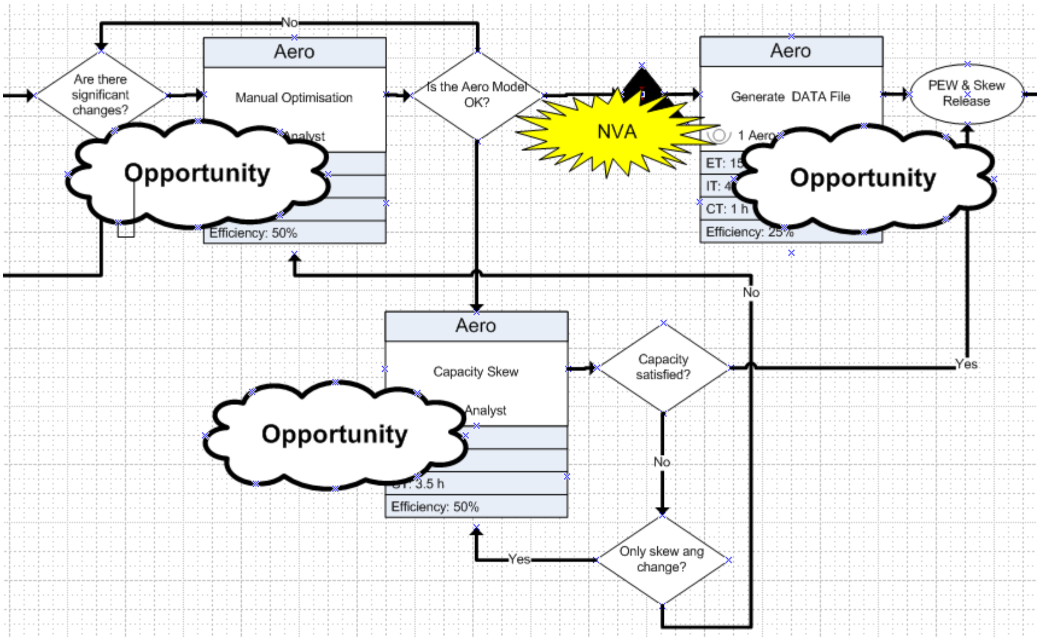
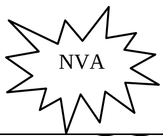
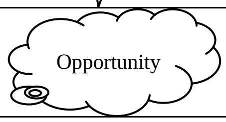
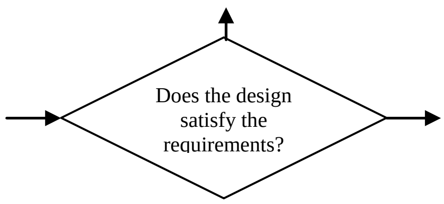
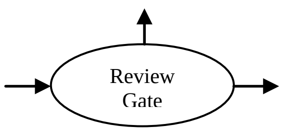
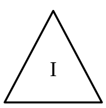



*Figure 7. VSM example*

*Table 2. VSM symbols description*

| **Symbols[4]** | **Description** |
|---|---|
|   | Kaizen burst represents a waste/ non value added in the process. As described in Section 2.2 these waste types can have several forms. |
|   | Opportunity cloud represents an opportunity for improvement, possibly an activity with a low efficiency that can be improved. |
|   | *Iteration symbol* shows that a particular loop of activities or an activity is done several times, such as 3 times on this example. |
|   | *Decision gate* represents the moment in the process where a decision has to be made. The question can be “does the design meet the customer expectations”. If the answer is yes the design continues, in case of negative answer a redesign would be planned.<br>The decision gates can also be used to define what analyses should be done considering some results. For example if the stress results are very high a more demanding life assessment has to be made, otherwise a much simpler analysis can be done to declare the component life. |
|   | *Review gate* represents the moment in the process where a formal and exhaustive check of design is done to assure the design is good enough to pass to next design stage. The review gate can also originate a redesign loop if the design doesn’t meet the customer requirements.<br>In between two review gates there are several decision gates. |
|   | The *inventory symbol* represents information stopped in the process. This can happen for several distinct reasons such as waiting for signatures, approvals, department policies, etc. |

[4] Some of these symbols are also described in McManus’ manual [9].

The VSM representation identifying the information flow and the main waste types in the process will support the next steps in the improvement process. In order to scope the improvement process, the VSM can be done at a higher level in the first instance. Having the high level VSM it is possible to understand where the design process bottlenecks are and where the improvement will have a more significant impact in the overall lead time of the design process.

## 3.4 Critical Areas Identification

As mentioned before, the identification of critical areas should be done by analyzing and discussing the VSM with the main stakeholders of the improvement process. The main stakeholders at this point are the end users of the design process, the improvement solutions developers and the senior management. The main objective of this discussion is identifying the areas where the end users have more difficulties, making sure that the solutions for these problems can be addressed and that there is senior support for that work. The difficulties can be seen in terms of lack of human and IT resources, lack of training, new tools needed, lack of understanding of the process, etc.

This discussion should conclude by identifying the main problems of the process and having the priority list for improvement. This priority list should be defined considering the main stoppers of the process and should have the buy-in of senior management stakeholders.

Presenting the VSM helps in the development of a general understanding of the design process and promotes the brainstorming of ideas to address the least efficient areas of the process which contributes to the prioritization of the improvements.

## 3.5 Design Structure Matrix (DSM)

The VSM is really useful and effective when representing simple and linear design processes. However when representing complex product development processes, the VSM is more effective when applied in conjunction with the DSM. The DSM represents numerous iteration loops and activity dependencies which characterize complex product developments which are not feasible to show on the VSM without adding complexity and making it difficult to read. Considering the graphical message of the VSM (one of its main benefits), it was decided in this research to leave it as simple as possible, showing in an easy way the process time inefficiencies and using the DSM to manage the iteration loops if needed.

The information needed to develop the DSM is captured on the data collection sheet (described in Section 2.2). The principles behind the DSM are explained by Whitney and others in [3], therefore this paper only includes a very brief explanation of what can be done using the DSM.

The DSM is normally a squared matrix, having the rows and columns populated with the activities names, as represented on Figure 8. Each dot on the matrix represents a dependency between two activities. This dependency can be represented in several ways, but the method used on this research defines the dot as a dependency of the task on the row, which means the activities on the row, are dependent of the activities on the column.

Analyzing the matrix, it can be understood that a linear and sequential process only has dots on the lower part of the matrix diagonal. In other words, all the dots above the matrix diagonal represent iterations and the further the dot is from the diagonal the longer the iteration loop is. The principle of the DSM is reorganizing the sequence of activities to reduce the iteration loop durations, which cannot be done with the VSM.

On the DSM example (Figure 8) there is a long iteration loop, identified with a kaizen burst that could be reduced or eliminated by reordering the activities or introducing extra activities. This example came from a real engineering process where the DSM discussion led to the decision of introducing more check points in order to reduce the size of the iteration loop.

An additional detail that can be useful is to introduce the time data on the matrix diagonal. However considering that the time data is already on the VSM, this detail was disregarded on this research.

Note that the DSM is not always needed; from the experience gained on this research it is suggested that the decision on whether or not to use DSM should be made after analyzing the complexity of the iteration loops in the design process under improvement.

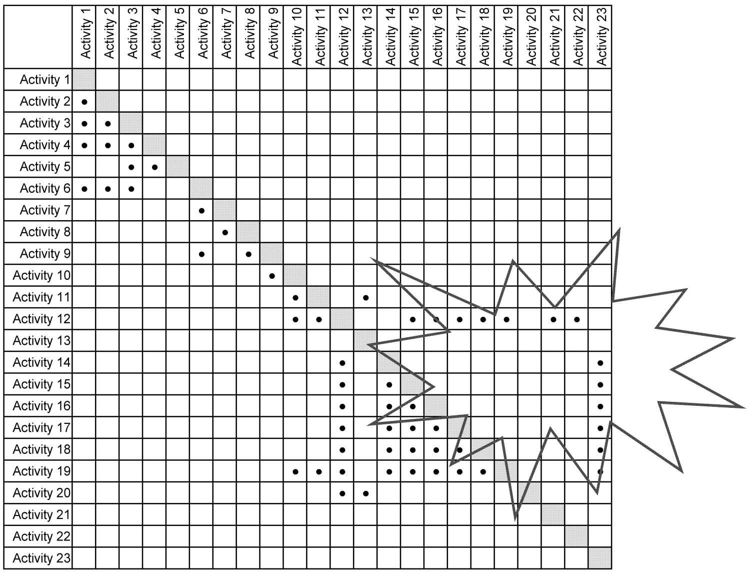



*Figure 8. DSM example*

## 3.6 Simulation

The main objectives of the simulation step are to understand the process lead time and the sensitivity of this lead time when improving parts of the design process.

Simulating the design process allows the improvement effort to be focused on the critical path activities; it helps to understand if the waste and the inefficient activities, identified on the VSM, are in the process critical path. It helps to understand the effect of reorganizing the iteration loops, prompted by the DSM, by simulating this reorganization. Furthermore simulating the elimination of the Lean waste in different scenarios (*what if* scenarios) provides a clear understanding of the impact of each potential improvement action. The output of this step is essential when discussing the required funding for improvement with top management because it shows the benefits that can be achieved for a certain investment within a certain confidence interval.

The Cambridge Advanced Modeler (CAM) is the software used to simulate the process in this research. This tool allows the introduction of three time values collected for each activity – the longest, mode and shortest time durations – which is extremely important to deal with uncertainty in analysis in which the exact time of the activities is sometimes extremely difficult to estimate. Simulating the different design process scenarios using a triangular time distribution identifies the most probable overall duration.

In addition, analyzing the variability in activity times identifies the main sources of variability of the process which should be reduced or eliminated to assure a controlled process (being a controlled process with a predictable output). From this research experience, the design team members always say that an activity duration depends on several things. For planning purposes the impact of having an activity taking 2 weeks or 2 months can be crucial, therefore the main sources of variability should be identified and reduced.

Summarizing, having the process map simulated using the stochastic data allows several analyses such as:

- The design process lead time distribution, showing what the minimum, maximum and the mode lead times are.
- The design process capability, understanding if the process meets the required lead time and how significant is the process variability to me meet the process requirement.
- The aforementioned *what if* scenarios, analyzing single or simple combinations of improvements.
- Finally, using a Design of Experiments (DOE), the best combinations of improvements can be analyzed. DOE, in this case, can be defined as the variation of combined activity durations to understand which lead to the most significant improvement.

### 3.7 Future VSM

The recommended approach to develop the future VSM is discussing the current VSM, the DSM and the simulation results with the main stakeholders, analyzing the potential improvement and comparing it with the improvement effort.

Once agreed, the improvement and respective waste elimination should be simulated and represented on the VSM and DSM.

The future state should be characterized by:

- Balanced work load for human and computational resources, considering the right training is supplied
- Reduction and, if possible, elimination of waste.
- Standardization and, if possible, automation of manual processes.
- Re-organized iteration loops to minimize effect of planned and unexpected iterations on the process lead time.

In the first instance this state is only an estimation that should be validated after the improvement solution is in place. The future state should also be used to plan, track and measure the improvement.

## 4 CASE STUDIES

The first case study was focused on the High Pressure Turbine Blade (HPTB) for a gas turbine. The HPTB design process must reconcile the following requirements: providing the required thrust, minimizing cost, minimizing weight, minimizing fuel consumption, etc. For these reasons the blade design is one of the most challenging tasks when designing a gas turbine. The goal of this first case study was to improve the design process, particularly by identifying opportunities for automation. The High Pressure Turbine Disc (HPTD) system was the focus of the second case study. The turbine disc's main function is to locate and retain the blades while transferring the rotational force they generate to the shaft. The disc has to be designed to withstand a specific number of flight cycles being submitted to enormous centrifugal loads exerted on the disc by the mass of the blades rotating at high speed. Moreover the discs are considered critical parts of a gas turbine, because a disc failure may have hazardous effects on the engine [1]. The main challenge of the HPTD design is in demonstrating during prelim design that it will ultimately meet the customer requirement for component life. The lifing assessment is a time-consuming part of the disc design process and tends to be done in a later phase of the process which doesn't leave a lot of time for optimization activities. All of this makes it extremely important to reduce the HPTD design process lead time.

### 4.1 High Pressure Turbine Blade Detailed Design

The aim of this case study was to improve the detailed design phase of a High Pressure Turbine Blade (HPTB). The HPTB is one of the most demanding components in terms of design due to the demanding environmental conditions the blades suffer. During the research the main activities included engagement with the team and their work and developing the framework as described in [5].

The Integrated Project Team (IPT) comprised 9 people representing 6 different functional areas and an IPT leader. To engage with the team the author had several informal and formal discussions with the team members and attended their internal meetings. The team was working at that time on the detailed design phase of the blade development. The design process is classified, in Rolls-Royce, as conceptual design, where a large number of concepts are assessed by a specialized team (Future Programmes Engineering), as preliminary design, where a more accurate design assessment is done and during a detailed design phase.

One of the highlights of this study was the workshop where the process map was put together and the critical areas were identified by considering the main problems identified by the IPT. Discussing the process map made it clear that the process was very complex and should be scoped and prioritized.

Another point to stress is the importance of using the DSM when discussing the dependencies between activities that were not visible on the process map or VSM. Using and discussing the DSM made it possible to show a long iteration loop that could be easily avoided by having interim aerodynamic assessments.

In order to make sure that the solutions discussed were useful and feasible, the last session was held, aiming to discuss the improvement solutions and respective implementation. This discussion of the VSM and DSM, involved the IPT and those responsible for developing automation tools. This session followed the structure described on [5]. Several improvement solutions were raised in this session (Table 3):

*Table 3. Improvement solutions discussed and respective impact*

| Examples of Improvements discussed | Overall Lead Time Reduction |
|---|---|
| Incorporate manual checks on the automated optimization | 11.76%[5] |
| Automate manual data translation | 1%[5] |
| Improve management of releasing new automation tools | 4%[5] |
| Automate verification of surfaces | 4%[6] |
| Simultaneous mechanical and aero validation | 10.4%[6] |
| Develop a parametric model to accommodate geometry changes | 7%[6] |

[5] Real Lead time reduction (improvements already implemented)
[6] Potential lead time reduction estimated by experts

The improvements discussed would introduce an overall lead time reduction of approximately 500-hours which corresponds to 38.2% reduction in the lead time.

### 4.2 High Pressure Turbine Disc Prelim and Detailed Design

This second case study has two main goals, firstly to validate the improvement framework developed during the first case study and secondly to assess the framework usability at system level and for different design stages. As a result of this study, additional steps were already introduced to the framework, such as the simulation step, which was shown to be an essential tool when negotiating the budget for improvement.

The High Pressure Turbine Disc (HPTD) is one of the critical parts of a gas turbine, which means that the disc failure will potentially have a hazardous effect on the engine. When making a formal bid, Rolls-Royce commits to its customers that the engine can be flown for a defined number of flight cycles without needing significant maintenance. If a major component such as the HPTD needs to be replaced before the engine has reached the agreed number of flight cycles then the company may be liable to pay penalties to the customer as compensation. The long lead time of the HPTD design process can mean that all the allocated design time is spent ensuring the life requirement is met but little or no time is available for optimization of other attributes such as cost and weight.

In order to address this problem, several process map capture sessions were held, resulting in a very complex process map of the prelim and detailed design phases of the design process for the disc and associated system. Further discussions were held to capture the high level engineering manufacturing activities and respective interfaces with the design activities.

Following this step, the individual structured interviews to collect the VSM and DSM data were completed. Eleven team members, representing the different functional areas were interviewed. The data collected allowed development of the current high level VSM. This VSM showed that the percentage of value added time in the process was less than 20%, the other 80% being non-value added or required non-value activities.

This brief analysis demonstrated the scale of the improvement opportunity. To progress the improvement, a process simulation was undertaken. Several scenarios were simulated and discussed:

- Simulation using the actual processing time data with the current human resources. This analysis showed that the process lead time was in the order of several months and so a significant improvement would be required to enable the process to be done in a matter of days, as necessary to allow the disc design to be optimized.
- Simulation using the processing time data but unlimited human resources. It showed that increasing the human capacity wouldn't be enough.
- Simulating the process using the core time. It showed that even if it were possible to eliminate all the non-value added and required non value added activities, it wouldn't be enough to achieve the required improvement. From this analysis it was possible to conclude that even the value added activities should be improved.
- After these simulations, several other scenarios were simulated considering only one hypothetical improvement at a time, to prioritize the improvements list and define an improvement plan.

From these analyses, it was possible to understand that there were two distinct but significant areas for improvement; the "model generation" activities (CAD model, thermal model, stress model, etc) and all the activities needed to calculate the disc life once the models are in place (defined as "geometry to life" activities). From the simulation, it was clear that the "model generation" and "geometry to life" activities were contributing equally to the overall duration of the HPTD design process. Considering that there were already several initiatives to accelerate the model generation activities, such as the parametric models generation, this research focused on improving the "geometry to life" activities. Note that the improvement of this part of the process is extremely important if several iterations are required to optimize a certain design concept.

To improve the "geometry to life" activities, a detailed process map and VSM were developed to assure that the waste hidden within value added activities was identified. As described in [9], often non value added activities are hidden within tasks that are value added. On these maps, the activities were represented at a tool and people level; different tools and/or different people implied a different activity. The detailed VSM constituted 29 activities, the Processing Time to complete these activities once is 24.5 days, of which only 48% is value added time this means there is a potential to reduce the lead time by 52%. The main sources of waste described in the VSM were discussed and from this discussion a list of improvement actions was put in place. The main problems identified were manual data handling between spreadsheets (more than 20-hours), lack of IT capability (40-hours and costing some quality compromise) and tools standardization. After this discussion several data handling activities were automated, the IT capability was improved and several opportunities for tool development are under discussion. Saying this, it should be noted that there is still space for continuing the improvement in this design process.

## 5 CONCLUSIONS AND FUTURE WORK

This paper describes the development and validation of a framework for improving engineering processes, demonstrated on two case-studies. From the two case studies it was possible to understand the benefits of using this methodology and test the usability in a real engineering environment.

The first case study highlighted the lead time reduction and the interface management improvement that can be achieved using the framework. The second case study helped to further develop the methodology making it applicable for real engineering environments, introducing the simulation to support management discussions. Simultaneously, it allowed the framework utilization to be assessed for different design phases and at a system level, once it was applied to the HPTD system level for both prelim and detailed design phases. This framework is currently being used to support methods and automation work in Rolls-Royce. Results showed a potential improvement of 50% in process lead time along with a significant improvement of the design quality.

Further work is undergoing on the stochastic analysis, the aim of this analysis is to analyze the process stability, identifying and reducing the main sources of variability in the process.

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