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KEY PROCESS VARIABLE DRIVEN MANUFACTURING PROCESS SELECTION

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1. Introduction

Significant effort is being made within the aerospace sector to reduce the unit cost of components and increase the material utilisation within formed and forged engine components. It is estimated that around 70% of manufacturing costs are determined during conceptual design stages [Smith et al. 2010], in some cases, manufacturers may have buy-to-fly ratios of less than 20%, prompting questions as to whether the most efficient process is being selected in the design stage.

There is a lack of objective manufacturing process pre-selection techniques, and subsequently, a need for a quick, broad and comparative study using key variables to evaluate potential manufacturing processes, with the intent of down-selecting and prioritising these processes. In the majority of cases, engineers trust their experience in selecting the process for the manufacture of a specific component. However this may result in bias and preference of processes and materials being key drivers for their selection. As a result, optimal manufacturing processes; some of which may be new and emergent technologies, can be overlooked, simply because of the gap in knowledge in terms of process capability and applicability. Over the last 20 years in particular, research in this area has resulted in the development of a range of methods, which attempt to improve the procedure of manufacturing process selection.

Shercliff and Lovatt [1998] and Ashby et al. [2003] have produced notable works on process selection. Both agree that there are three different types of selection strategies, loosely based on the stages of the design process, i.e. conceptual, embodiment and detail design stages [Shercliff and Lovatt 1998]. However, it is suggested that a selection task is one of these three types, whereas Ashby et al. imply that a combination of approaches are required in order to obtain the most accurate and feasible outcome. Each selection task is different, so by singling out one approach, the risk of over-constrained selection and missed opportunity is significantly higher. Process selection should be carried out in the early stages of the design process when considering aspects of design for manufacture, since this where the majority of costs are determined [Smith et al. 2010].

A flexible, adaptable decision-based methodology has been developed following the work structure illustrated in Figure 1. In contrast to previous research, the methodology presented within this paper does not work under the assumption that each selection task should be approached in the same way. Instead, design requirements are translated in a logical manner, are case dependant, subsequently providing the criteria for selection. Appearing simplistic, the methodology is underpinned by hidden complexities that filter all possible manufacturing processes into a set of viable contenders applicable to the specific component, allowing selection of the most efficient process.

2. Investigation

Ashby et al. [1992] developed the Cambridge Engineering Selector, the only commercially available selection software. The focus is primarily on materials, although there are some elements of process selection, but the principles are based purely on well-rounded decision making for selection. The system translates design requirements, filters through potential solutions, and produces a manageable set of potentially viable answers that are provided with supporting information. Ashby is also widely recognised for developing graphical methods, including the Ashby Plot and the Ashby Chart [Ashby 1992].

Mathematical methods have been proposed by many, including Raviwonsge et al. [2000] and Kohara et al. [2009], who attempt to quantify the decision making process. These strategies incorporate methods such as Self-Organising Maps and the Analytical Hierarchy Process. Despite their intended use for selection tasks with a level of uncertainty, Hayes and Akhavi [2008] argue that mathematical methods are not as widely used as expected, and do not necessarily improve problem solving performance. A more effective strategy would be to better reflect the human decision making needs, while avoiding the need for a lengthy process.

Some methodologies studied rely on specific attributes being pre-defined prior to the selection task being carried out [Cogun 1993], namely material and production quantity, or have a set order for requirements to be considered. This can be seen as a somewhat contradictory factor considering the desire to create a flexible system.

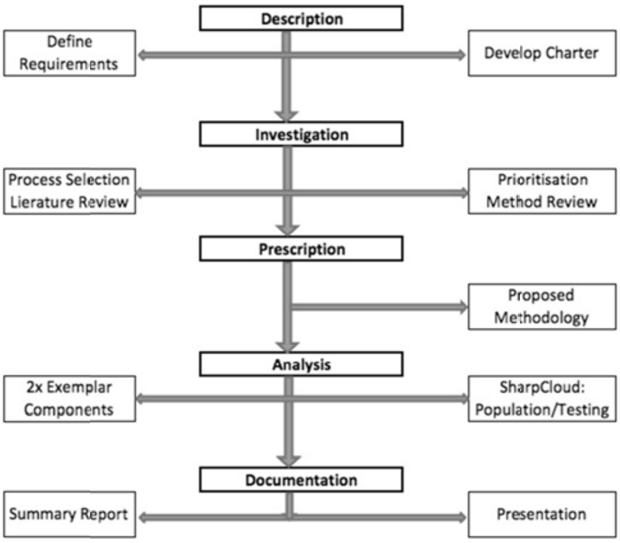

Figure 1. Project methodology

2.1 Prioritisation methods

Creating an adaptable methodology requires integration of methods which can be used to aid the translation of design requirements into selection criteria. It can be argued that no matter which order questions are asked, the same answer will result. Decision makers must have a need to use the methodology, in order for it to be successful. To be used it must appear viable to the decision making team – with *justifiable* results. This can be addressed by considering selection criteria in a logical order, reflective of the end requirements of the design previously set.

A variety of different methods for prioritisation exist, eight of which were analysed, compared and considered for use as part of the investigation stage. The method does not need to be exhaustive, nor does it have to provide a complex output, all that is required is that it is simple, and quick to carry out. Reasoning behind designing a methodology like this is partially to cut down on the overall time and/or ensure focus in the areas that need it.

2.2 CARVER method

CARVER is a method originally developed by the US Special Forces, used in planning for both target selection and identifying potentially high risk targets. Although devised for a different application, the principles can be adapted and used to generate a matrix, highlighting which elements are most immediately necessary and what should come later. CARVER is an acronym, as described in Table 1.

Table 1. CARVER method

Criticality	Criticality with respect to the main objective?
Accessibility	Do we have the resources/capability? Immediate start or are there prerequisites?
Return	Greatness of expected return?
Vulnerability	Vulnerability of requirement? Risks?
Effect	Impact upon fulfillment of the aim? Wider effect?
Recognition	Is the requirement clear? How easy is it to recognise the required steps?

2.3 Conclusions from investigation

It has become evident that existing research has identified a requirement for a simplistic, yet functional strategy that will provide comprehensible results, while steering the decision maker away from preference and bias choices – a quality that has become contradicted in some cases. It seems that many of the discussed proposals, although recognised, have resulted in complex and time-consuming processes, expensive systems and services, or requiring significant analysis effort; not exactly a driving factor in encouraging use by decision makers. Derived from the investigation stage is a re-emphasis of the need for a quicker, broader methodology for manufacturing process selection.

3. Proposed solution

Following the initial research phase, it had become clear which elements of previous methods were suitable, such as the combination of approaches proposed by Ashby [2003], and those which were less successful, such as the mathematical approach proposed by Raviwonsge et al. [2000]. This helped to define what exactly, in the context of this work, the characteristics of the methodology being proposed should be. The primary requirement is to create something which would use process attributes to carry out broad comparisons and support the evaluation of multiple manufacturing processes.

A notable issue with some of the current process selection methodologies is that there is a lack of flexibility. The proposed methodology should have the ability to be easily tailored and adapted dependent on the task in hand. Each task subject to manufacturing process selection will be different, and different outputs will be required, e.g. in some cases, perhaps the surface detail is the driving factor, whereas others may be focussed on geometric precision. Having set criteria for selection would be presuming that each task working through the methodology has the same level of requirements, often not the case, so by allowing for a degree of flexibility, it can be much more focussed and specific.

3.1 Methodology

The proposed methodology, shown in Figure 2, tackles the issue of manufacturing process selection in a different way. Essentially, the core function is to be the means of converting a set of inputs - the requirements, into a set of outputs - the selection of a process [Ashby et al. 2003]. More specifically, it is a transition from the set of all manufacturing processes, to a manageable sub-set which can then be considered. A sub-set as an outcome is more realistic than one mathematically optimised solution - a sub- set of processes will facilitate the decision maker(s) in making an informed choice rather than making the decision for them. This may take into account factors such as accessibility to equipment.

A key requirement is to address the lack of flexibility, common in existing process selection methods. The proposed methodology is flexible as a result of two main attributes:

1. The overall structure,
2. The way in which requirements are considered.

Starting with the overall structure: the methodology primarily flows horizontally, although is also segmented vertically. Each of the vertical sections, termed *Levels* divides the process into more manageable portions, and can be added, removed and tailored as required. These levels question different task-dependent requirements.

Underpinning the main Levels is the pre-selection groundwork or *Level 0* as it has become known. Level 0 is illustrated with a much clearer divide than the others - considerable focus was in these initial stages as it is the foundation for which the remainder of the selection process is built. Any design activity, including any potential alterations or improvements required before the selection task is carried out here. Clear definition of this stage helps to eliminate the risk of it being omitted; it can often be tempting for decision makers to jump to a conclusion based on their expertise and preferences.

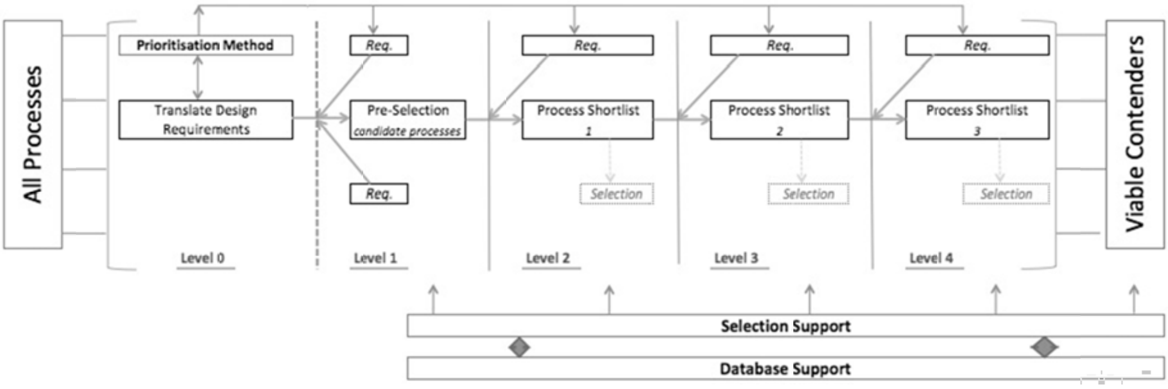

Figure 2. Down Select Methodology

3.1.1 Level 0

The methodology then focusses on how to translate the design requirements of a specific task into selection criteria. This could be approached in multiple ways; however, clarifying the second of the flexibility attributes, is the decision to incorporate a prioritisation method. Logically, the method will prioritise the part requirements in order of their importance respective of the final output. These will then feed the input factors vertically into each Level. The most crucial aspects are also likely to be the most discriminating in terms of process suitability, according to [Shercliff and Lovatt 2001], these are the questions that should be asked first. This will also ensure than there is a clear 'funnelling down' throughout the progression of the process. Fewer processes will then remain to be assessed on the more complex requirements of the part.

The CARVER method, selected for its simplistic nature, has the ability to be used in a number of ways; it could be completed by one, a small group or a team of people. How it is approached could also vary, perhaps a team will carry out the method individually before collating and discussing their answers, or maybe it is part of a teamwork focussed exercise. There is scope for stakeholders to work with this in a way that suits their needs, as well as fitting in with the context of the task in hand.

The values given to each of the requirements with respect to the CARVER attributes are collated and summed within an Excel spreadsheet template, resulting in a prioritised scoring. This provides the basis for Levels 1-4 of the methodology. The key requirements identified will be ordered as selection criteria within.

A collaborative meeting is held within the prioritisation stage involving relevant stakeholders, in conjunction with the initial generation of the part or product specification. It is referred to in this work as a *Stakeholder Symposium.* There are potentially other benefits that this could promote, particularly in terms of customer focus and satisfaction. Customers would have a clearer understanding of the correlation between their expectations and what is actually realistic. It would help encourage them to consider what features actually *need* to be included, and those that perhaps do not matter as much. Essentially, it can help to ensure that all stakeholders are clear and in agreement to the expectations and requirements prior to the selection task and subsequent work being carried out.

This activity is crucial. Conventionally, stakeholders will give a specification; and manufacturing engineers will select a process. The main issue is often the lack of an in-depth consideration and rationalization of why a particular process was selected. Alternatives are commonly not considered, contradictory of the fact that design in general is open-ended; design engineers need the willingness to consider all possibilities [Ashby 1992]. This method ensures that multiple processes are analysed.

There is a lack of discussion and involvement of the stakeholders within the decision making task. Ultimately, they are the judge as to whether a manufacturing task is successful or not.

3.1.2 Level 1

Level 1 can be considered as being the pre-selection stage - this is the level where the processes that are *clearly not feasible* can be eliminated. Input in this stage is the highest scoring requirements (two are shown in Figure 2) previously identified in the prioritisation method. These factors will be the most discriminating in selection, so the majority of processes will be disregarded, leaving a smaller set of candidate processes to follow through to the next stages.

3.1.3 Levels 2-4

The levels which follow can be added or removed as required for the specific task. Levels 2-4 will foresee a more gradual funnelling down process, taking into consideration the more specific requirements, and resulting in a refinement of candidate processes each time. These requirements may be categorised, e.g. *Economical Requirements*, with an underlying set of more detailed needs which can be considered during progression of the level.

These levels work vertically as well as contributing to the overall horizontal flow of the methodology, resulting in focussed attention given at each stage. It is also possible that the decision makers could result in a confined enough shortlist after any of these levels, although four is recommended.

3.2 The significance of levels

The levels are more than just a means of dividing the process into more manageable stages.

Generic decision making tools for process selection have an input factor, and an output factor - but lack in detail where the transition is concerned. It is clear that there are issues, which have been attempted to be solved, although many have failed to direct decision makers away from the tool that they know ‘works best’: their own preference. This is precisely what this methodology is attempting to address.

The level breakdown prompts consideration for the steps in-between achieving the A – B objective in selection. Decision makers have an element of control over the filters used to down-select. Breaking down the process encourages evaluation at each stage, perhaps a problem may arise, things may have changed - it is much simpler to go back a level, particularly as each stage is recorded, than starting from the beginning again.

Furthermore, it is in the nature of engineers and designers to question things: why are things the way they are? Where did those solutions come from? Particularly as the majority of design tasks are open-ended, with no set answer – designers seek rationale. A logical systematic approach is needed, one that is robust in the decisions made – this is the logic behind the consideration of requirements on different levels. The process down-select problem has only been left un-solved because decision makers do not use past solutions. Incorporating the level structure allows for them to see, but more importantly *understand* and *justify* where each of the answers (in this case process short-lists) are coming from. As a result, the methodology will appear reliable, and a desirable contribution to decision making.

“Creating effective decision aids is not simply a matter of finding a method that computes the most correct answer or the interface that best presents the data, but also of finding the most effective way to integrate tools with the human problem solving needs.” [Hayes and Akhavi 2008, p. 153]

3.3 Selection Support

From a user perspecitive, a methodology of this nature should *appear* simple, although requires supporting hidden complexities. The first of these has already been discussed in the prioritisation method, however crucial to the decision making framework is the Selection Support.

The key requirements of the selection support is that it is able to capture the capabilities of a broad range of manufacturing processes while enabling decision makers to filter these, using the criteria defined during the prioritization method. Although not the primary focus of the project, consideration of selection support was critical, particularly in allowing the methodology to be demonstrated.

Figure 3. SharpCloud

For experimentation purposes, SharpCloud was the selection support tool used; software allowing for the creation of visual experiences to communicate a story [SharpCloud 2013]. The stories help to convey the overall view (Figure 3), with the integration of timelines, relationships and virtual worlds being some of the features that help these stories stand out and provoke visual appeal. It provided a broad comparison of a wide range of manufacturing processes based on different process attributes, such as finishing costs and cycle times, although other tools can be used to undertake the same task.

3.4 Database Support

Giachetti [1998] identifies the significance of incorporating both decision and database support within the process selection methodology. Databases of technical and process data underpin the selection support. Again, another hidden complexity, databases should be updated frequently, ensuring a reliable source of information. Some previous selection methods have revolved around either selection or database support, but not collaborating the two. As illustrated in Figure 2, the database support is shown to work in two directions. Not only is the process data essential for process selection to take place, it should also be subject to feedback as a method of selection – adding to the database and analysing where necessary upon completion of manufacturing tasks. Over time this will capture past-case data, potentially useful and applicable to future selection tasks, and even for compiling case studies. The supporting database can be as simple or as sophisticated as needed. In this case, it was generated within an Excel spreadsheet, data can easily be imported and exported from an Excel file, and can be easily integrated into different selection support tools.

4. Exemplar Components

Demonstration of the proposed methodology is critical in justifying its logic. Described below is an example use case based on an aerospace application. There are, however, a potentially large range of applications of the methodology due to its adaptability depending on the task; the approach discussed can also be used for more generic parts.

4.1 Engine Shaft

Shafts are central components to the aero-engine, running through the majority of the length, and are required to connect and mount other parts. As a result, it is critical that they have high strength and structural integrity. Continuous effort is being made to manufacture them thinner and resultantly more lightweight to help reduce fuel and other costs, but also stronger. These characteristics could be considered contradictory, so the key to achieving the objective lies in the design process, namely in the selection of the best manufacturing process. This is a prime example of cost reduction in aerospace components, the main driver for this project.

An example part specification of a typical engine shaft has been drawn up for demonstrative purposes:

- Must be manufactured from high strength material, Titanium/Nickel based super alloys common but in this case, high strength steel will be used for its integrity and toughness.
- Geometric requirements are that the part is tubular, of varying cross sections with a flanged end.
- Material utilisation should be excellent, main aim is to reduce material waste.
- The part requires a smooth surface detail to be fit for purpose.
- Finishing costs should be minimal, secondary processing should be avoided.
- Good process flexibility to allow for similar components of varied sizes to be manufactured using the same technique.
- Overall quality should be excellent, close tolerances and high mechanical strength necessary.

Level 0

Although the requirements of a component with the caliber of an aero-engine shaft tend to be greatly detailed and specific, it is used for demonstrative purposes, not to solve a problem, hence the generic nature of the specification. As the methodology describes, the specification is broken down and prioritised using the CARVER method, Table 2, to produce an order for the requirements to be considered in selection.

Table 2. CARVER Analysis

	C	**A**	**R**	**V**	**E**	**R**	**Total:**
Material	5	4	3	4	2	3	21
Geometric Requirements	5	5	4	5	2	4	25
Material Waste	5	5	5	3	5	3	26
Surface Detail	5	3	4	2	4	4	22
Finishing Costs	4	3	5	2	4	5	23
Flexibility	2	4	2	3	3	4	18
Quality	4	4	3	5	5	4	25

The results from the CARVER matrix are then fed into the methodology, resulting in a model tailored to the specific manufacturing task.

Level 1

Material waste/utilisation and overall part quality were the factors used in Level 1, the stage where the majority of processes which are clearly not viable will be eliminated. After filtering within the SharpCloud system taking the processes with the lowest material waste and highest quality, the candidate process list, consisting of 19 processes was generated – derived from the original 45.

Level 2

The next highest scoring requirement is considered within Level 2. In this particular case, it can be seen that there are in fact two attributes with the second highest score. Decision was made for the geometric requirements to solely dominate Level 2 due to the fact that it is essentially a *set* of requirements. This approach to filtration worked well due to the tag feature within the system; the 19 candidate processes were shortlisted to 10.

Level 3

Working with the 10 processes of the first shortlist, Level 3 considered the processes with the lowest finishing costs, and higher surface detail values. This resulted in a further process being eliminated to form the second shortlist.

Level 4

The remaining processes were filtered depending on their changeover flexibility and applicable materials. Two manufacturing processes, considered "viable contenders" resulted. This is a prime example of where an informed choice is required. In this case, one of the two processes, flow forming, is superior in terms of surface detail, so is the selected process.

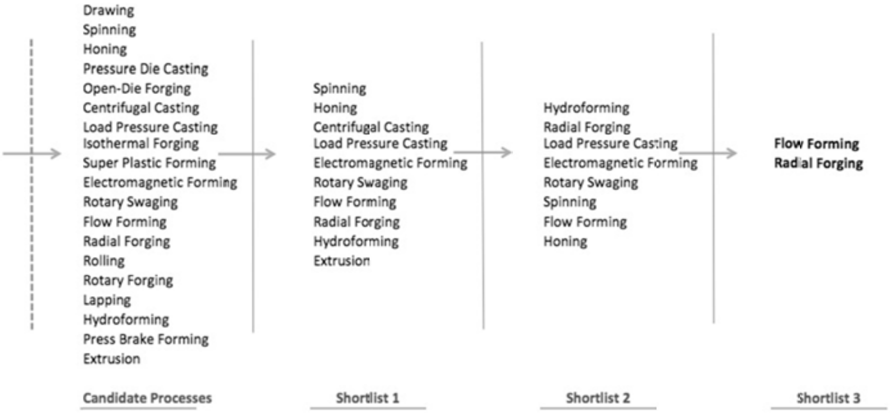

Figure 4. Down Select Results; Engine Shaft

Summary

Manufacture of an engine shaft is an ideal example of an aerospace component where continuous effort into part cost reduction and improved buy-to-fly ratio is being made. Selection of better manufacturing processes can significantly improve the part prospects. In this example, a generic engine shaft has been used, which after following the methodological steps resulted in flow forming being the best process for the task, one which is subject to research and development work for potential use in critical mainline engine shafts.

Recording of the results after each level of selection, as seen in Figure 4, is critical when using SharpCloud as the selection support. The system allows for advanced filtering of the processes, although filters are limited in terms of how many can be applied at once, so some processes eliminated in Level 1 may reappear in Level 3. Keeping track of the shortlist allows decision makers to ignore these processes and continue with the selection task. If more detailed input attributes were to be used, use of the system may be unfeasible.

5. Recommendations

Process selection is a fundamental issue in design for manufacture of aerospace components. The research carried out within this project reinforced the evident complexity of the issue. As a result, the main recommendation is that the work carried out to date is continued, building upon the findings presented in this report. This project focussed on the development of the decision-based, selection methodology proposed, but what is needed in future is focus on the support tools embedded within, for instance, the selection and database support. There is clear opportunity, and with such applicability and need within industry, the potential exists to further develop a valuable process-selection tool.

5.1 Specification Translation

Further research is required within the pre-selection stage, more specifically when extracting design requirements. Specifications take a variety of formats and level of detail, resulting in potential inconsistencies where the down-select method is concerned. The specification is the root of the overall process, and is the document which can determine much of the cost and final outcome of the part. Translation of the specification will involve stakeholders and decision makers, clearly defining the requirements and expectations, as well as simultaneously prioritising these to facilitate process selection. What must be considered, however, are potential conflicting criteria and the risk of two or more attributes being rated the same in terms of importance. Incorporation of a secondary tool or tailoring of the current method to address the possibility of this occurring could be a further development. Further work should begin with emphasis on these underlying aspects.

5.2 Process Chains

Net-shape manufacture is becoming increasingly sought-after, however in the majority of cases, parts require a sequence of manufacturing steps before being considered finished. Perhaps in some instances it is not simply the selection of the most efficient manufacturing process: what if the combination of steps is the key to improved selection? Research into this possibility would prove challenging, requiring greater detail of work, and possibly an alternative selection support tool. It may be unrealistic to capture every potential combination, but perhaps selecting the core process first, followed by selection of the *best* pre- and post-processing techniques could be effective. Feasibility of this approach would need to be explored.

5.3 Material Selection

Process and material selection are undeniably linked. Some existing methods researched look at the potential co-selection of both materials and processes [Giachetti 1998], [Smith et al. 2010], [Albiñana and Vila 2012], where others work on the basis that the material is a predefined attribute [Cogun 1994], [Swift and Booker 2003]. Examination into the viability of incorporating a material selection tool could be useful. Some cases may require a specific material type or grade to be used, but others may not be so certain, with only the qualities of the required material being defined. Research into the correlation of process and material selection could also contribute to the overall cost-reduction aim. What cannot be ruled out is that perhaps the most efficient material is not being selection for the same reasons as the processes – preference and bias. In addition, this could potentially increase the flexibility of the method, ensuring that it can be used in as many scenarios as possible. Component cost reduction is a problem that is by no means one-dimensional. There are a number of factors that contribute; addressing as many as feasible within a methodology would be advantageous.

6. Conclusions

The process down-select project undertaken at the Advanced Forming Research Centre allowed for considerable progression to be made in understanding the issue of manufacturing process selection, specifically within aerospace engine components, despite only being the initial stage within a larger project. Research into significant works of literature in the area combined with identification of the key requirements and awareness of the underlying issues resulted in the generation of a conceptual selection methodology.

The proposed methodology is one that tackles the process selection task in a unique way. Traditionally, the selection methodology is a transfer function between the input of part requirements, and the output of selected process(es). This is also true of the proposed solution; however the differentiating factor is the breakdown of the selection task, as well as the decision maker's ability to tailor it for each individual selection task. By incorporating different levels, the decision makers are encouraged to focus more effort into the pre-selection phase, where they involve input from stakeholders to define and prioritise the requirements for selection. More importantly, it allows for the decision makers to *understand* and *justify* where each of the answers (in this case process short-lists) are coming from. As a result, the methodology offers traceability and supports rationalization by the decision-maker. By developing a methodology which supports the human decision making process in this way, it reflects the engineer's nature to question things, supporting its potential for successful adoption. The levels also allow for evaluation at each stage, meaning that if circumstances change or a problem occurs, it can be addressed as it arises.

Simplicity is desirable in selection methodologies, although it is evident that it should *appear* simple, and requires underlying hidden complexities. The nature of the project required a broad comparison approach, and SharpCloud software was used to achieve this. It provides the selection support, and allows user to visualize the task for a clearer understanding. Decision makers also need to keep track of the process shortlists due to the filtering limitations within SharpCloud.

7. Future work

Although developed to a high level at this stage, the methodology presented within this paper has clear potential to be further refined and utilised as the basis of a more detailed process selection method. What this project has enabled is the justification of the feasibility of developing a process down selection method for use within the aerospace sector. There is scope for the development of a purpose-built toolset, incorporating both database and selection support, subsequently eliminating the reliance on existing systems. In turn, this will allow the methodology to accommodate selection tasks of a higher complexity. Relevant examples will be required to effectively test the process selection toolset in its entirety, particularly in parts which best represent the process selection challenge.

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