INTERNATIONAL DESIGN CONFERENCE – DESIGN 2024
https://doi.org/10.1017/pds.2024.51

Evaluation of a multi-user requirements axiomatic design decision support tool for manufacturing process selection

Edward Abela ✉, Philip Farrugia, Pierre Vella, Glenn Cassar and Maria Victoria Gauci
University of Malta, Malta
✉ edward.abela@um.edu.mt

Abstract
Manufacturing process selection presents numerous challenges to designers, including product complexity, consideration of production volumes and part tolerances. This paper introduces a design support tool based on the axiomatic design model to systematically transform requirements into functions and technological capabilities. The results from an evaluation of the implemented prototype tool in the field of medical device design demonstrates its usefulness in selecting the most suitable candidate manufacturing process for a given artifact, while taking into account multiple user requirements.

Keywords: early design phase, axiomatic design, requirements management

1. Introduction

The initial phases of product design can pose significant challenges for designers when it comes to Manufacturing Process Selection (MPS) (Kersten et al., 2018). This necessitates dedicated design support to aid designers in taking informed decision to select a manufacturing process. While various researchers concur that MPS should be addressed in the early stages of design (Eddy et al., 2019; Hernández-Castellano et al., 2019), the lack of support for MPS during the initial task clarification stages can influence how the primary design problem is formulated (Fiorineschi et al., 2016). Moreover, when requirements from various stakeholders are not clearly defined, design specifications tend to be incomplete (Yip et al., 2019). Thus, it is crucial to incorporate multi-user requirements during MPS to ensure alignment between the selected process and the goals and needs of diverse stakeholders (Abela et al., 2023). In industries like medical device manufacturing, a diverse pool of stakeholders including healthcare professionals, regulatory authorities, and engineering designers, is highly relevant to ensure the device meets the intended requirements of all parties involved.
When multi-user requirements are mapped onto the relevant design parameters and process variables, design engineers can deploy an informed MPS strategy (Abela et al., 2023). By systematically incorporating manufacturing information into the Axiomatic Design (AD) model, a solid basis can be established to assist designers in choosing the most suitable manufacturing technologies for producing a product that caters to the needs of multiple users (Abela et al., 2023). A previous study was conducted by Ferrer et al. (2009), whereby designers generate design parameters (DPs) based on identified functional requirements (FRs) and then make decisions to select the optimal process based on these parameters, even though no reference to the non-functionality aspect of the product is made. Nonetheless, it is worth noting that the technology capabilities of fabrication technologies, such as machine tolerance levels and part resolution, are often overlooked during the early selection process. Thus, it can be argued that by assessing these capabilities, designers can be precisely guided to choose the most appropriate process from a pool of potentially valid alternatives suitable for manufacturing the

product. For instance, through a case study of a 3D printed release-buckle for an upper-limb rehabilitation device, Abela et al. (2023) have showed that by taking into consideration capabilities early during MPS, such as those corresponding to the printer's material capabilities and surface roughness capabilities, designers may obtain a clear picture of which additive manufacturing process is mostly suited to fabricate the component. In this case, various functional requirements (locking, releasing) and non-functional requirements (durability) were central to the MPS.

In this research paper, we evaluate a prototype tool intended to assist designers in the task of MPS by facilitating the requirements elicitation process and making direct reference to mapping the machine's capability to fabricate the artefact being designed. A boundary on the repository of manufacturing processes was placed such that the MPS is restricted to AM fabrication processes. The presentation of the prototype tool is structured around the **AXI**omatic **DE**sign for **M**anufacturing process selection (AXIDEM) model which was introduced in our previous work (Abela et al., 2023) and which proposed a model oriented towards the design of rehabilitation products. The remainder of this paper is organised as follows: Section 2 provides an overview of the related research, focusing on the support for MPS in design, while also highlighting the research gap and criteria used for the tool's evaluation. Section 3 offers a high-level representation of the AXIDEM model, which draws upon axiomatic design principles, but goes further by considering multi-user user requirements and technology capabilities. Section 4 discloses the results obtained from the evaluation of our computer-based tool. This evaluation involved input from a number of product development stakeholders. These results are then discussed in Section 5. Lastly, Section 6 draws the conclusions from the current study, emphasising the contribution of this work and makes various recommendations for future research.

2. Background and related work

A systematic literature review was conducted to explore existing research models and methodologies that support MPS as early as the task clarification stage in the design process. The review was based on the guidelines formulated by Kitchenham & Charters (2007), our research question revolved around how designers are supported in selecting the most appropriate manufacturing process based on the identified requirements for the artifact being designed. The different approaches examined were categorised as method-driven, knowledge-based, data-driven and decision-support approaches.

Method-driven approaches employ structured methodologies and frameworks to assess, score and select manufacturing processes. This type of approach enables designers to synthesise and evaluate processes and make informed decisions. The key advantage of this approach is its reliance on objective criteria, such as production rate, dimensional accuracy, surface finish, rather than solely depending on a designer's intuition and experience. For instance, various method-driven models, such as Ferrer et al.'s (2009), rely on the AD model to formalise Design For Manufacturing (DFM) and manufacturing process information which the designer can easily access. This approach involves identifying process attributes such as tolerance levels and part roughness and mapping them onto execution variables, which are variables defining the technology capability of the process. AD-based models can incorporate information tables related to existing processes during MPS, including design rules, regulatory considerations, and Design for Manufacturing and Assembly (DfMA) guidelines. However, a limitation is that product requirements specified in AD-based models are often determined by the designer, who remains the sole user of the model. Other method-driven models may serve the purpose of establishing weighted scoring for each capability criterion to facilitate process ranking (Liu et al., 2020) of different manufacturing processes or performing part classification to tailor towards specific user requirements (Wortmann et al., 2019).

Formal knowledge plays a critical role in supporting MPS during the initial stages of design (Lee, 1992) particularly in knowledge-based approaches. Ontology-based methodologies, such as that proposed by Nagy et al. (2021), revolve around identifying process elements and utilising knowledge graphs to model information pertaining to different processes through the use of semantic web applications. *Case-Based Reasoning* (CBR) has also been noted to facilitate MPS (Mabkhot et al., 2019) by structuring process knowledge within ontologies and to evaluate lessons learnt in manufacturing. Ontologies are significant since these use open-source tools to support different types of capability datasets. Meanwhile, they facilitate graphical representation of processes and capabilities by providing visual information to designer in terms of tolerances, surface finish, part weight, wall thicknesses and material specifications, captured within the ontology. Nonetheless, ontology based models such as those developed by Nagy et al. (2021) and Mabkhot et al. (2019) do not prioritise part application and process relevance. Additionally, modifications and alterations in customer requirements and product specifications during the design process are not reflected within the OBS, whilst only the designer-user is considered whose expertise in the field of ontologies is expected.

Giachetti (1997) states that the MPS challenge often represents decision-making problem characterised by ambiguous requirements and parameters in the preliminary design stages. According to Minguella-Canela and Buj Corral (2020), decision support for MPS involves making choices which related to process capabilities, market demands, and production constraints. Such decisions are taken on the basis of manufacturing knowledge and experience that exist in design domains. Many decision support systems incorporate rules for assessing manufacturing processes derived from expert systems, as demonstrated by Park & Tran (2017). Others make use of machine learning to populate a corresponding knowledge base during the selection process, such as in Zhang et al. (2014). Such models make assessments in terms of tolerancing and accuracy, but the machine's capability based on the artefact's surface finish, roughness or biocompatibility is not assessed. The AM technology is selected based on the part quality and material selected, but no consideration to production volume, geometrical complexity or mechanical properties is given. Alternatively, systems like the one proposed by Byun & Lee (2005) employ fuzzy-logic to learn specific features incorporated into the selection process, however these are highly subjective process requiring input from domain experts to obtain a more objective decision-making process.

Other data-driven approaches, as exemplified by Ge (2018), focus on extracting manufacturing information from industrial systems and transforming it into relevant knowledge. Techniques such as data mining are used, whereby process and product data is stored in large databases and knowledge is extracted to support the decision-making process for MPS. As shown in Agard & Kusiak (2005), similar processes can be clustered together and evaluated in terms of tooling, temperature, cutting and speed capabilities. This may however restrict MPS to the available in-house processes and relies heavily on historical patterns and historical data in manufacturing.

Various researchers recognise the significance of early-stage MPS. However, there is a notable lack of adequate support tools available to designers to conduct such activities. Existing models often reply primarily on functional requirements formulated by designers themselves. Literature underscores the importance of integrating both functional and non-functional requirements (NFRs) during product design (Hernández-Castellano et al., 2019; Thompson, 2013) arising from multiple stakeholders (Fleury & Chaniaud, 2023). Therefore, based on the reviewed literature, a gap in research exists in supporting manufacturing process selection based on multi-stakeholder interests incorporating both functional and non-functional requirements during early-stage design. The AXIDEM model, described in the next section, is aimed to address this gap.

3. AXIDEM: A prototype implementation for MPS

The high-level representation of the AXIDEM model, presented in Figure 1, seeks to support designers in obtaining a better understanding of the limitations and capabilities of different manufacturing technologies available. This allows designers to map the relevant design parameters onto the ideal candidate manufacturing technology, hence reducing the number of design iterations further down the line. The main objective of the AXIDEM model is therefore the systematic decomposition of the design process, mapping Customer Needs (CNs) directly onto process variables by means of axiomatic mappings. The AXIDEM model is structured into five distinct design domains; the *Customer Domain*, the *Functional Domain*, the *Physical Domain*, the *Process Domain*, and the *Technology Domain*, all linked to a User Requirements Repository (URR) and a Manufacturing Knowledge Repository (MKR). The URR provides a basis for the CNs/FRs mappings whilst the MKR serves as a repository for storing manufacturing knowledge such as DMFA standards and guidelines which guide the designer to make considerations, regarding the efficiency of the assembly and the ease of manufacturing.

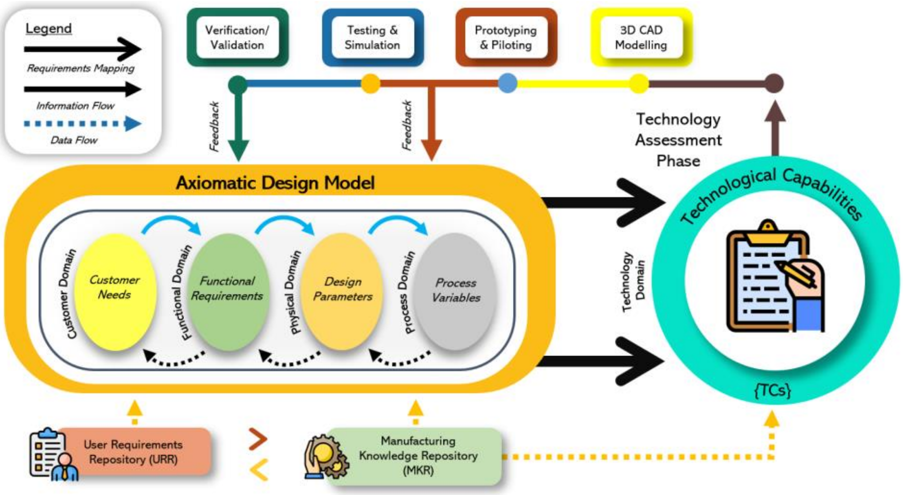
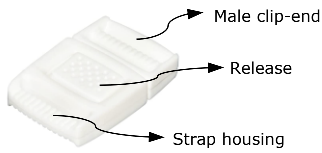


Figure 1. A high-level representation of the AXIDEM Model

The *Customer Domain* encompasses the needs of the customer. CNs are mapped onto functional/non-functional requirements using constraints, which define solution restrictions and limitations. FRs and non-functional requirements (NFRs) collectively shape the device's performance and behaviour. These requirements should be as minimal as possible and independent. In the *Physical Domain*, FRs and NFRs are then translated into design parameters (DPs). These are measurable elements describing the design's physical aspects. DPs specify individual units to fulfil the device's functions, such as in terms of specifying locating units, clamps, or base plates for accuracy and stability. Table 1 depicts the mappings of CNs onto FRs, and FRs onto DPs for the release-buckle case study mentioned in Section 1.

Table 1. CNs, FRs, and DPs mappings for the release-buckle case study

{CNs}	*Fastening mechanism*			
{FRs}	*Requirement*		*{DPs}*	*Parameter*
FR_1	Lock	→	DP_1	Tensile strength
FR_2	Release	→	DP_2	Shear strength
$(N)FR_3$	Withstand repetitive loading cycles	→	DP_3	Modulus of elasticity



DPs are further decomposed into process variables (PVs), which define manufacturing variables such as cost/kg, weight, size, surface roughness, tolerances, clearances, and part resolution. The *Technology Domain* involves the mapping of PVs onto technology capabilities (TCs), which quantify the characteristics of available manufacturing technologies. A correlation between manufacturing process variables and the technology's ability to meet the standing requirements is created by generating a technology capability score. This facilitates the comparison of available technologies for the specified application and hence is the main basis to conduct MPS. The URR serves as a dedicated repository for both FRs and NFRs, aiding in the collection, organisation, and preservation of these requirements during the design process (Jaksic et al., 2022). The MKR contains a repository of *explicit knowledge* (such as PVs formulated by the user) and *tacit knowledge* (such as guidelines based formulated in line with ISO13485 and ISO14971 standards). Proper usability management throughout the design process is ensured by making considerations under the guidance of IEC 62366 (ISO, 2015). Following the technology selection phase, the AXIDEM model can make suggestions on the classification of the medical device being designed prior to initiating the modelling stages.

3.1. Proof-of-concept Implementation of AXIDEM

In order to implement and evaluate the applicability of the AXIDEM model, a computer-based proof-of-concept tool was developed. The user interface of the tool was developed through *Visual Basic for*

Applications (VBA). VBA's advantage lies in its functionality as an event-driven programming language (Milicevic et al., 2013). This feature provides a high-level of responsiveness to the user's actions and enables trigger events based on the user's interactions with the interface, such as selecting specific requirements or accessing particular menus (Yadav et al., 2014). Upon launching the tool, designers are greeted with an initial user form, enabling them to input the product's requirements for the artefact they intend to design. Once the product mapping process is initiated, the primary interface is presented to the designer (see Figure 2).

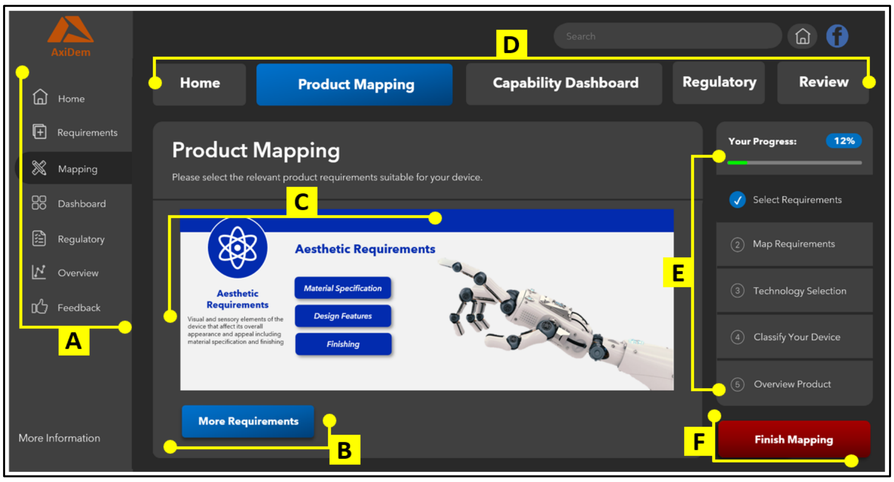


Figure 2. Main GUI of the AXIDEM prototype tool

The main menu, illustrated in area **A**, provides designers with access to various tool elements. Areas **B** and **C** are designated for input of the requirements by the designer. In area **C**, designers can define specific product parameters, which, in this case, pertain to the aesthetic requirements of the product. Additionally, other requirements, including manufacturing requirements, performance specifications, and surface finish criteria, can be selected by clicking on area **B**. These requirements were formulated around various studies conducted with different stakeholders, including healthcare professionals, medical device designers, and patients, given the AXIDEM prototype tool is oriented towards the design of rehabilitation products (Abela et al., 2022). Areas **D** and **E** provide an overview of the ongoing progress in the requirements mapping process.

3.2. Retrieval and mapping of requirements

A set of *requirement elements* which are loaded from the URR can be selected by the user to start the mapping process. The retrieval of each element follows the algorithm below:

```
Sub Retrieve_Requirement_Element()
    selectedRequirement = AXIDEM.Sheets("requirement elements").Range("A1").Value
    Set reqDataSheet = AXIDEM.Sheets("URR_req_data")
    Set requirement =reqDataSheet.Columns("A").Find
    What:=selectedRequirement, LookIn:=xlValues, LookAt:=xlWhole)
End Sub
```

where *A* and *A1* refer to references within *URR_req_data* repository, and are replaced by the specific location in the repository of the different requirements. For each requirement input generated by the user, the MKR updates the list of PVs residing in the repository. This list of PVs is preset in the tool and updated based on the *requirement elements* inputs specified by the user. Alternatively, the list of PVs in the MKR can be updated by formulating new variables when defining a new requirement. The list of PVs is associated with a library of available manufacturing technologies. Based on the requirement specified by the user, the list of PVs within the MKR is updated to reflect this requirement. This serves as an input to the *technology capability* matrix. Inputs to the matrix are based on the PV/TC mappings, determined by specifying the capability of each technology in meeting the formulated PVs. In this case, a set of rules are applied for each PV to determine whether the capabilities for technologies are fulfilled or not. The algorithm below illustrates how the *technology capability* matrix is updated in the MKR based on the user's selection and the capabilities of individual manufacturing technologies. The generic term *techCapabilities* is used to represent a generic TC element.

```
Set techCapabilities = MKR_mappings.Range("A3:A37")
For i = 1 To techCapabilities.Rows.Count
    For j = 1 To techCapabilities.Columns.Count
        If MKR_mappings.Cells(i + 1, j + 1).Value = userSelection Then
            techCapabilities.Cells(i, j).Value = 1
        Else
            techCapabilities.Cells(i, j).Value = 0
        End If
    Next j
Next i
```

where TCs are listed in cells A3:A37. The algorithm retrieves the user's selection of the requirement from the *URR_req_data* repository and updates the *technology capability* matrix in the *MKR_mappings* repository based on whether the user's selection matches the capability of each technology.

3.3. Capability scoring for MPS

For each variable stored in the MKR, a set of IF-THEN-ELSE rules describe the capability of the different technologies to satisfy the corresponding PV. This generates a matrix of TCs being mapped from the defined PVs. Once the designer is satisfied with the specifications in the product mapping interface, the designer is directed to a capability dashboard. This provides an overview of the technology capabilities mapped against the specified requirements. A suggestion is made to the designer with regard to the ideal candidate process for the application as shown in Figure 3.

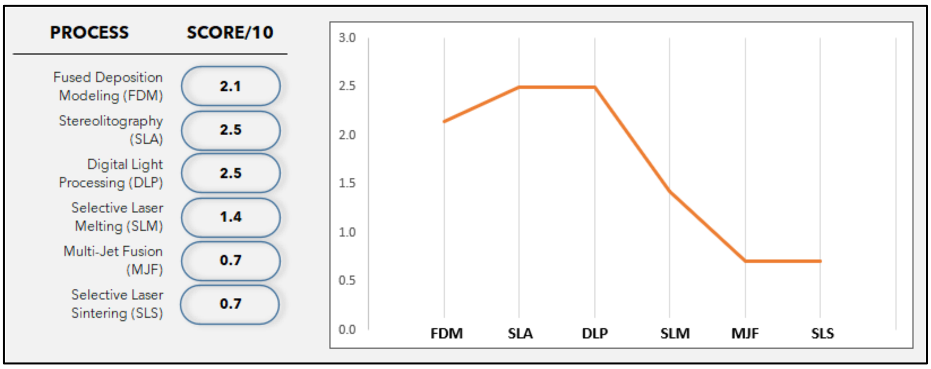


Figure 3. Scoring system and MPS recommendation within the AXIDEM model

4. Evaluation of the AXIDEM tool

The primary assessment of the AXIDEM tool focused on evaluating of its principles with users from the engineering design industry. To address the research question outlined in Section 2, a set of evaluation objectives were formulated to investigate to what extent are designers:

1. supported in mapping both functional and non-functional requirements during the task clarification stage of the product design process;
2. guided in mapping multi-user requirements onto the appropriate manufacturing processes through AXIDEM;
3. supported in exploring candidate manufacturing processes through the AXIDEM model;
4. assisted in selecting the most suitable manufacturing process amongst other alternatives to fabricate the corresponding product being designed.

4.1. Sample of participants

The evaluation was composed of semi-structured interviews with a total of 20 participants, listed in Table 2. Convenience sampling was used to recruit participants. Recruitment was done mainly through

LinkedIn and also by commissioning the *Austrian Center for Medical Innovation and Technology* (ACMIT), and *Kinisiforo Ltd & Nicomed Rehabilitation Center* (KNRC), find suitable designers to participate in this study. The sample size of 20 participants may be considered small since it can limit the generalisability of the findings (Tipton et al., 2016). However, this sample size falls within the acceptable range as recommended by Creswell (1998), who suggests that a sample of 20-30 participants is suitable for interview-based healthcare-related studies. In addition, Vasileiou et al. (2018) remark that a point of saturation is reached at around 20 participants when conducting a thematic analysis, meaning that no novel concepts emerge for assessment. Hence, this sample size is deemed sufficient for the evaluation. Another challenge pertained to issues to confidentiality and intellectual property (IP), since many designers were hesitant to share propriety information concerning the design processes they adopt and the tools they use in their work.

Table 2. Recruited participants, background and country of origin; **YoE: Years of Experience*

	YoE*	Background	*Country*		YoE*	Background	*Country*
P1	15-20	*Medical device design*	Austria	***P11***	5-10	*Design and AM manager*	Cyprus
P2	5-10	*AM designer*	Austria	***P12***	0-5	*Prosthetics & Orthotics*	Cyprus
P3	0-5	*Surgical device development*	Austria	***P13***	20+	*Chief Product Officer*	Cyprus
P4	15-20	*Designer, Patient-specific tools*	Austria	***P14***	20+	*Head of Medical Product*	Cyprus
P5	15-20	*Sr. Designer manager*	Austria	***P15***	15-20	*Director of Design*	Cyprus
P6	5-10	*Product development manager*	Italy	***P16***	20+	*Company owner, P&O*	Cyprus
P7	0-5	*Product manager*	Italy	***P17***	20+	*Design release engineer*	Cyprus
P8	5-10	*Design manager, design training*	Italy	***P18***	5-10	*Design Enterprise manager*	Cyprus
P9	0-5	*Team leader in AM design*	Italy	***P19***	0-5	*User requirements & design*	Malta
P10	5-10	*Product design & manufacturing*	Italy	***P20***	0-5	*Design Researcher*	Malta

4.2. Protocol

Prior to conducting the interviews, participants received a thorough overview of the AXIDEM model, including an overview of how requirements are mapped within the model. The underlying principle of how MPS is conducted based on the various input requirements was also explained to the participants. A demonstration of the tool prior to starting the interviews was given the participants through a case study so that they could understand better the tool's potential. A semi-structured interview was then prescribed to each participant individually. In total, each interview lasted an average of 60 minutes. All interview sessions were recorded and transcribed verbatim to facilitate the analysis of the information collected. A pilot study was also carried out beforehand with two academic researchers. This led to a number of modifications to wording and terminology whilst several questions were added, such as "*Would you use the tool in the design of rehabilitation healthcare devices?*". In order to absorb better the participant's feedback and their experience in the field of healthcare design, a mixed-methods approach was adopted, whilst a thematic analysis was carried out. This allowed for the collation of identity patterns within the collected data and a better understanding of the phenomena. The thematic analysis adhered to the guidelines provided by Braun & Clarke (2006).

5. Results and discussion

5.1.1. Theme 1: Benefits of AXIDEM compared to current design practice

A notable 90% of respondents confirmed that they adhere to formal design models in their current design practice. However, none of the surveyed participants mentioned the axiomatic design model as one of the models they use. The majority of participants either strongly agreed (85%) or agreed (10%) that the AXIDEM model could support the design processes they currently employed in their design work. Respondents mentioned a number of advantages in using the AXIDEM model as part of their design work. P2 mentioned that the model increases the designers' awareness of processes available for during MPS. Additionally, P1 emphasised that "*the consideration of multi-user requirements is missing in the general design world*", whilst P8 highlighted that "*the model can bring many advantages to the workplace, especially with replacing traditional manufacturing processes with newer ones*". By taking into account a broad range of capabilities such as machine tolerances, surface quality parameters, and material capability, designers can refine the fabrication process and the design of the artefact to meet specific product requirements. All respondents agreed that the multi-user requirements approach adopted in the AXIDEM model is beneficial as it helps to implement all stakeholder and business needs, and also since the model supports in providing a bespoke solution to the user, as stated by P9.

5.1.2. Theme 2: Requirements mapping using axiomatic design

All participants which had direct experience often of more than five years working in the medical industry eemphasised the need for early-stage design support in MPS. During the evaluation, 25% of participants stressed the importance of traceability between the design stages. P3 commented that the "*traceability of the device should feed back to the original identified requirements*". This suggests the need for a clear and documented link between the identified requirements and the various stages of the product's lifecycle. In general, the model's ability to assist in the generation of robust solutions and in providing a structured approach to the design of medical devices was commended. P11 explained that this model "*presents alternative technologies that can have more beneficial aspects in the manufacturing selection process*". This was a point agreed upon by other participants (such as P6) based around the notion that the model supports the decision-making process of the designers by making them aware of various manufacturing considerations, such as material selection, production volume and machine capability to fabricate the product at the required part clearances and tolerances. Participants were satisfied with the ability to map both FRs and NFRs onto the appropriate design parameters.

5.1.3. Theme 3: Provision of support during MPS

Participants were asked to what extent they find it difficult to incorporate the interests of multiple stakeholders during the early design phase for MPS in their current practices. Respondents remarked that this was either very difficult (50% of respondents) or difficult (40% or respondents) whilst it was observed that participants engaged in the design of patient-specific tools and surgical devices (P1, P3 and P4) found it more difficult to incorporate multi-user requirements. This is attributed to the complexity and specificity of the needs of the individual patient and those of healthcare professionals (such as doctors and surgeons) participating in the design. A noteworthy distinction was made between MPS for off-the-shelf products and bespoke products. The activity of MPS for bespoke rehabilitation devices is normally a more challenging task (P10) due to individualised end-user requirements and the complexity of medical injuries and conditions being addressed. Participants emphasised the need for MPS support based around the manufacturing capabilities of the available fabrication techniques related to lead times, product cost and design restrictions. The integration of a feedback loop in the AXIDEM model was considered advantageous. This was highlighted because existing design models commonly used in industry, such as stage-gate processes, are often limited in this regard, as noted by P4.

5.1.4. Theme 4: User-friendliness and practicality of the AXIDEM tool

Participants were questioned to gauge their perceptions regarding the ease-of-use, convenience and operability of the tool. In this case, 90% of respondents highly agreed (60%) or agreed (30%) that the tool is easy to use and understand. One main benefit observed lies within the tool's intuition to support the designer in "*taking decisions in the early design stages*" (P20). In terms of the willingness to use the tool, all participants agreed that they would try it out as part of their design practice, however the point of tool validation was reiterated several times. The tool has to be compared to existing solutions to observe differences in outcomes, prior to application in industrial practice. Respondents commented that the tool could help in "*implementing new designs and in keeping track of material flow*" (P8). P9 suggested that designers are encouraged to use the AXIDEM as it "*provides a good basis in interpreting the requirements and in simplifying MPS at early design*". The tool's ability to consolidate requirements and assist designers in understanding candidate processes for MPS was also highlighted. When providing feedback on the practicality of the tool, 55% highly agree, while 35% agreed that AXIDEM is practical for use in design practice. Designers explained that the tool offers a platform for a more stratified and clear representation of each design parameter. P13 stated that the tool is "*highly practical since it provides you with various regulations and standards which one should follow*". While feedback suggests high practicality in design practice due to the tool's ability to provide designers with regulations and standards to be followed during product design, it is worth noting that the tool's practicality might be constrained since equipment and technology costs are not being directly mapped in MPS.

5.1.5. Theme 5: Improvements towards a software tool

The final theme of the collated feedback revolved around desired improvements in the AXIDEM tool. Participants suggested providing an opportunity to the designer to insert qualitative requirements to provide a more comprehensive mapping of DPs, PVs and TCs. Whilst the tool could have "*more parameters installed*" (P11), the qualitative feedback gathered suggests that even though different process parameters apply for different manufacturing technologies, designers should easily identify such parameters to support MPS through the AXIDEM tool. In terms of functionality, the tool could include the ability to input additional variables, such as material compatibility, cost, and scalability, in order to secure the final outcome for process selection. In view of the ability for MPS support, P11 highlighted the limited processes available for selection, which were restricted to AM.

6. Conclusions and future work

In this paper, the results from the evaluation of the AXIDEM prototype tool were presented. The results showed that the AXIDEM model has the potential to enhance the design process by accommodating diverse requirements arising from various stakeholders and by supporting the selection of manufacturing processes. Through the AXIDEM tool, the model provides a basis to map both the FRs and NFRs of a product arising from diverse stakeholders by taking into consideration the technology capabilities of fabrication processes available to the designer. Future work could focus on adapting the AXIDEM model and the prototype tool to manufacturing processes beyond AM. Further validation of the AXIDEM prototype tool is required before the tool can be implemented in industrial practice.

Acknowledgement

The authors wish to acknowledge that this research has been supported by the EU's Horizon 2020 research and innovation programme under grant agreement N° 856998 (Prime-VR2). The authors would also like to thank all the participants who contributed in this study.

References

Abela, E., Farrugia, P., Gauci, M., Vella, P., Cassar, G., & Balzan, E. (2022). A Novel User-Centred Framework for the Holistic Design of Therapeutic Medical Devices. *Proceedings of the Design Society*, *2*, 1199–1208. https://doi.org/10.1017/pds.2022.122

Abela, E., Vella, P., Farrugia, P., Cassar, G., Gauci, M. V., & Balzan, E. (2023). An axiomatic design methodology for manufacturing process selection based on multi-user requirements mapping. https://doi.org/10.14733/cadaps.2023.S6.62-74

Agard, B., & Kusiak, A. (2005). Data Mining for Selection of Manufacturing Processes. *Data Mining and Knowledge Discovery Handbook* (pp. 1159–1166), https://doi.org/10.1007/0-387-25465-X_54

Braun, V., & Clarke, V. (2006). *Using thematic analysis in psychology*. https://www.researchgate.net/publication/235356393

Byun, H. S., & Lee, K. H. (2005). A decision support system for the selection of a rapid prototyping process using the modified TOPSIS method. *The International Journal of Advanced Manufacturing Technology*, *26*(11), 1338–1347. https://doi.org/10.1007/s00170-004-2099-2

Creswell, J. W. (1998). *Qualitative inquiry and research design: Choosing among five traditions* (pp. xv, 403). Sage Publications, Inc.

Eddy, D., Krishnamurty, S., Grosse, I., & Steudel, M. (2019). Early design stage selection of best manufacturing process. *Journal of Engineering Design*, *31*, 1–36. https://doi.org/10.1080/09544828.2019.1662894

Ferrer, I., Rios, J., & Ciurana, J. (2009). An approach to integrate manufacturing process information in part design phases. *Journal of Materials Processing Technology*, *209*(4), 2085–2091. https://doi.org/10.1016/j.jmatprotec.2008.05.009

Fiorineschi, L., Frillici, F., & Rotini, F. (2016, January 1). *Re-Design the Design Task Through TRIZ Tools*.

Fleury, S., & Chaniaud, N. (2023). Multi-user centered design: Acceptance, user experience, user research and user testing. *Theoretical Issues in Ergonomics Science*, 1–16. https://doi.org/10.1080/1463922X.2023.2166623

Giachetti, R. (1997). Decision Support System for Material and Manufacturing Process Selection. *Journal of Intelligent Manufacturing*, *9*. https://doi.org/10.1023/A:1008866732609

Hernández-Castellano, P., Martínez-Rivero, M. D., Marrero-Alemán, M. D., & Suárez-García, L. (2019). Manufacturing Process Selection Integrated in the Design Process: University and Industry. *Procedia Manufacturing*, *41*, 1079–1086. https://doi.org/10.1016/j.promfg.2019.10.036

ISO. (2015). *IEC 62366-1:2015, Medical devices Part 1: Application of usability engineering to medical devices*. ISO. https://www.iso.org/standard/63179.html

Jaksic, D., Candrlic, S., & Poscic, P. (2022). From User Requirements to Document Repository Enriched with Metadata – a Case Study. *Procedia Computer Science*, *204*, 760–767. https://doi.org/10.1016/j.procs.2022.08.092

Kersten, W. C., Diehl, J. C., & Engelen, J. M. L. van. (2018). Facing complexity through varying the clarification of the design task: How a multi-contextual approach can empower design engineers to address complex challenges. *FormAkademisk*, *11*(4), https://doi.org/10.7577/formakademisk.2621

Kitchenham, B., & Charters, S. (2007). *Guidelines for performing Systematic Literature Reviews in Software Engineering*. *2*.

Lee, C.-H. (1992). *A knowledge-based systems approach for manufacturing process selection in design* [Ph.D.]. Ohio State University.

Liu, W., Zhu, Z., & Ye, S. (2020). A decision-making methodology integrated in product design for additive manufacturing process selection. *Rapid Prototyping Journal*, *26*(5), 895–909. https://doi.org/10.1108/RPJ-06-2019-0174

M. Mabkhot, M., Al-Samhan, A., & Hidri, L. (2019). An Ontology-Enabled Case-Based Reasoning Decision Support System for Manufacturing Process Selection. *Advances in Materials Science and Engineering*, *2019*, 1–18. https://doi.org/10.1155/2019/2505183

Milicevic, A., Jackson, D., Gligoric, M., & Marinov, D. (2013). *Model-based, event-driven programming paradigm for interactive web applications*. 17–36. https://doi.org/10.1145/2509578.2509588

Minguella-Canela, J., & Buj Corral, I. (2020). *Decision Support Models for the Selection of Production Strategies in the Paradigm of Digital Manufacturing, Based on Technologies, Costs and Productivity Levels*, IntechOpen. https://doi.org/10.5772/intechopen.89535

Nagy, L., Ruppert, T., & Abonyi, J. (2021). Ontology-Based Analysis of Manufacturing Processes: Lessons Learned from the Case Study of Wire Harness Production. *Complexity*, *2021*, https://doi.org/10.1155/2021/8603515

Park, H.-S., & Tran, N.-H. (2017). A Decision Support System for Selecting Additive Manufacturing Technologies. *Proceedings of the 2017 International Conference on Information System and Data Mining*, 151–155. https://doi.org/10.1145/3077584.3077606

Thompson, M. (2013). Improving the requirements process in Axiomatic Design Theory. *CIRP Annals - Manufacturing Technology*, *62*, 115–118. https://doi.org/10.1016/j.cirp.2013.03.114

Tipton, E., Hallberg, K., Hedges, L., & Chan, W. (2016). Implications of Small Samples for Generalization: Adjustments and Rules of Thumb. *Evaluation Review*, *41*. https://doi.org/10.1177/0193841X16655665

Vasileiou, K., Barnett, J., Thorpe, S., & Young, T. (2018). Characterising and justifying sample size sufficiency in interview-based studies: Systematic analysis of qualitative health research over a 15-year period. *BMC Medical Research Methodology*, *18*(1), 148. https://doi.org/10.1186/s12874-018-0594-7

Wortmann, N., Jürgenhake, C., Seidenberg, T., Dumitrescu, R., & Krause, D. (2019). *Methodical Approach for Process Selection in Additive Manufacturing*. *1*, 779–788. https://doi.org/10.1017/dsi.2019.82

Yadav, H., Paruthi, R., & Gupta, V. (2014). *Impact of Event Driven Programing Paradigm on Real World*.

Yip, M. H., Phaal, R., & Probert, D. R. (2019). Integrating Multiple Stakeholder Interests into Conceptual Design. *Engineering Management Journal*, *31*(3), 142–157. https://doi.org/10.1080/10429247.2019.1570456

Zhang, Y., Xu, Y., & Bernard, A. (2014). A new decision support method for the selection of RP process: Knowledge value measuring. *International Journal of Computer Integrated Manufacturing*, *27*(8), 747–758. https://doi.org/10.1080/0951192X.2013.834474