Computers in Industry 150 (2023) 103944

Contents lists available at ScienceDirect

Computers in Industry

journal homepage: www.sciencedirect.com/journal/computers-in-industry

# An uncertainty management framework to support model-based definition and enterprise

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ARTICLE INFO

*Keywords:*
Model-based definition (MBD)
Model-based enterprise (MBE)
Digital manufacturing
Digital thread
Uncertainties
Uncertainty management

ABSTRACT

In pursuit of industrial digitalisation, the manufacturing industry is going through a transformation in the methods for product definition from the traditional two-dimensional drawing to three-dimensional digital model known as the model-based definition (MBD). The real benefit of this digitalisation lies in the adoption of model-based definition across all stages of the product lifecycles throughout the enterprise and its supply chain which is termed as model-based enterprise (MBE). However, the current application of this technology is partial, due to the involvement of several associated uncertainties. This paper proposes a novel framework for the management of uncertainties in the adoption of the model-based definition and presents a system in support of the proposed framework. The development commenced with the collaboration of two major aerospace industries. The framework comprises five phases including the preliminary phase, identification, assessment, analysis, and response phase. A systematic process is followed in developing the framework while Numeral, Spread, Assessment, and Pedigree (NUSAP), and Analytical Hierarchy Process (AHP) are used in the assessment of uncertainties. The developed system consists of a user interface, a database of uncertainties, an assessment module, an analysis and prioritisation module, and a knowledge base of mitigation strategies for key uncertainties. The system facilitates the analyst to select the relevant uncertainties from a defined list, systematically assess and analyse each of the uncertainty and obtain recommendations for mitigation of the prioritised uncertainties in the project. The framework and the developed system were validated through expert interviews with two world-class aerospace companies. This system facilitates identifying the various types of uncertainties of MBD, quantifying their impact on the project rationally, and formulating a suitable management strategy for achieving the status of a model-based enterprise.

## 1. Introduction

The traditional form of product definition has been the two-dimensional drawing for an extensive period. This form holds very mature standards and well-established practices. The downstream documents within the product lifecycle such as process plans, assembly instructions, first article inspection reports (FAIR), maintenance, repair, and overhaul (MRO) instructions are also based on these drawings. The formulation and utilisation of these drawings and their associated documents require substantial time and effort along with the knowledge and expertise of the designer as well as the users down streams. Moreover, all these documents are created individually and have no digital thread across the lifecycle. Any changes at the design stage, therefore, result in excessive rework downstream which increases lead time and cost.

The advances in computer technology have created the possibility to present three-dimensional model as a substitute for traditional drawings by introducing computer-aided design (CAD) solutions. These three-dimensional models have initially been used for visualisation of product geometry only whilst the authoritative source for engineering activities has been the traditional two-dimensional drawings. Progressively, the evolution in the technology permitted inserting geometric dimensioning and tolerancing (GD&T) data as well as notes directly to the basic 3D CAD models (Quintana et al., 2012). Consequently, the 3D models began offering the capabilities to partly substitute 2D drawings in a few engineering functions. The recent developments are making it possible to embed semantic information with the basic model hence transforming these models into

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https://doi.org/10.1016/j.compind.2023.103944
Received 22 September 2022; Received in revised form 31 March 2023; Accepted 9 May 2023
Available online 30 May 2023

machine-readable models. However, these features are limited to discrete part manufacturing and inspection only. The current technologies cannot still incorporate product definition elements from the entire lifecycle stages of the product.

The future of this digitalisation process, however, is targeted at making product definition elements, from all the lifecycle stages, part of the digital model along with imparting semantic capabilities, and thus ensuring a digital thread, which is sometimes referred to as data from requirement to retirement (Alemanni et al., 2011). This defines the digitalisation of the product definition, the realisation of which is called a model-based definition. Model-based definition (MBD) is a three-dimensional digital model that is used for product definition encompassing all the product information across the lifecycle of a product. It is a sole and comprehensive source of product information and a replacement for the traditional drawing (Quintana et al., 2010). MBD captures the product data in digital format once and then allows other functions across the product lifecycle to reuse it (Astheimer, 2021). A model-based enterprise (MBE) is an enterprise that implements MBD as the sole authoritative source of data for all the engineering and business activities throughout the lifecycle of the product. This includes all the internal and external stakeholders that consume product data one of which is the suppliers (Frechette, 2011; Goher et al., 2021; Hedberg et al., 2016).

High-value manufacturing industries such as aerospace and automobile are the early adopters of model-based definition. However, the authoritative source of product definition for most of the internal and external organisational processes is still the traditional two-dimensional drawing. This is because there are several challenges and uncertainties in the way toward model-based enterprise (Goher et al., 2019). Though the application providers are introducing solutions at a very fast pace in this journey, the prevailing uncertainties and challenges are barring the complete realisation of the model-based enterprise.

The researchers have pointed out many challenges in application of MBD in the functional domains such as design, manufacturing, assembly, services individually and aspects like data, security and implementation (Bijnens and Cheshire, 2019; Briggs et al., 2010; Hedberg et al., 2017; Miller et al., 2017; Quintana et al., 2010; Ruemler et al., 2017), however, a systematic work for formulating a comprehensive list of uncertainties in adoption of MBD throughout the product lifecycle was missing. Furthermore, there is no work in proposing a systematic way to deal with all the uncertainties of MBD wholistically from the context of risk and uncertainty management. This research focused first on identifying and characterising all the prevalent uncertainties in the adoption of MBD. Secondly, it proposed a framework for the management of the identified uncertainties. The proposed framework involves five phases which are preliminary phase, identification, assessment, analysis, and response phases. A software system in support of the proposed framework is also presented. The framework is aimed at supporting the decision makers identify key uncertainties from the developed knowledgebase of uncertainties for the domain/domains of application considered for adoption of MBD. This work further presents a knowledgebase for mitigation of five highly ranked uncertainties which is a foundation step towards building a comprehensive knowledgebase of mitigation strategies for all the identified uncertainties of MBD. This work will benefit organisations aiming for digitalisation of product definition through consideration of all the related uncertainties in advance. This research work was carried out in collaboration between the School of Aerospace, Transport, and Manufacturing, Cranfield University, UK, and two world-class aerospace companies in the UK.

The rest of this paper is organised as follows. Section 2 presents the contextual theory while Section 3 presents the methodology adopted. The developed framework for the management of uncertainties of model-based definition is presented in Section 4 and the software system developed in support of the framework is presented in Section 5. Section 6 emphasises the validation of this work, while Section 7 covers results and discussion. Finally, Section 8 concludes the article and proposes future work.

## 2. Related research work

A product definition is a means by which the information which defines an object is structured and understood. Generally speaking, it is the sum of a variety of domain-specific definitions, while each domain has its unique requirements and way to specify the features of the product (Miller et al., 2017). Historically the designer communicates the product information to various domains in the production chain like manufacturing and inspection using two-dimensional drawings (Bijnens and Cheshire, 2019; Venne et al., 2010). These drawings contain various projection views which are annotated with dimensions, geometric dimensioning and tolerancing (GD&T), material specifications, and other data like version and revision history. With the introduction of a new technology recognized as model-based definition (MBD), the two-dimensional approach is now referred to as the traditional way (Bijnens and Cheshire, 2019; Quintana et al., 2010). Model- based definition offers replacement of these two-dimensional drawings with three dimensional digital models and thus creates a digital design. It uses these models for managing all engineering and business processes. These models are the single and complete source of product definition for design, manufacturing, distribution, technical documentation, services, maintenance, repair and overhaul (MRO), and in general, the overall product lifecycle. In MBD the model can be defined to address the requirements of all the downstream users such as procurement, tooling, manufacturing, assembly, inspection and testing, product services, maintenance, sales/marketing as well as the clients and the suppliers (Geng et al., 2014; Quintana et al., 2010).

MBD offers many benefits (Quintana et al., 2010; Ruemler et al., 2017; Venne et al., 2010) such as: improved accuracy of the work with all stakeholders, reduced costs and times of developing and printing the drawings, improved capability to effectively interrogate the models, improved data quality through offering a single source, elimination of the associativity issues between 3D models and 2D drawings, reduction of errors in design, reduction in manually produced data, and fewer files to maintain.

In the early model-based definition, the model only depicted the geometric properties. However, the technology is improving the ability to define products by enabling the product definitions to be more holistic. Researchers have started to explore the elements of a multi-viewpoint model, that takes into its account the requirements of various stakeholders and workflows within an organisation. However, it is still to be agreed upon that how these different domain definitions could fit and interact with each other, and be carried by the model (Miller et al., 2017, 2018). Eventually, information from all phases of the product's lifecycle is needed to be carried by the three-dimensional digital model so that it could represent and communicate the same level and quality of information that the two-dimensional drawing has been offering over the years (Ruemler et al., 2017).

The modern world is in a continuous transformation phase that is becoming more and more complex every day with the introduction of new and innovative technologies at a very high rate. The application of these technologies leads sometimes to new, unforeseeable issues and situations that cause doubts in their deployment. These issues and situations are termed uncertainties or risks. These uncertainties affect the decision-making process in the process of adoption of these technologies (Erkoyuncu et al., 2013). It is therefore critical to develop the capability to understand and manage the uncertainties to facilitate and support the decision-making process while adopting new technology (Goher et al., 2021b).

The terms risk and uncertainty are used interchangeably sometimes while there is a considerable difference between them. The rationale behind this is that uncertainty is the absence of certainty or a condition when the definite outcome or state cannot be established (Hubbard, 2010). An uncertainty could impact a project positively, negatively, or even neutrally, while the risk is a kind of uncertainty that only impacts the project negatively. In this article, the researcher has used the term uncertainty instead of risk. Risk has always had a negative impact and deals with only the outcomes. Uncertainty, on the other hand, concentrates on its source and the options to respond. Thus understanding and management of uncertainties can be used to shape effective organisational strategy (Ward and Chapman, 2003). The process of risk and uncertainty management has been explained by several resources which consist of almost similar phases. These are plan, identify, analyse, respond, and manage (A guide to the project management body of knowledge, 2017; ISO, 31000:, 2018*(En), Risk Management - Guidelines*, 2018).

There are several ways to identify the uncertainties. These include literature reviews, semi-structured interviews, brainstorming techniques, nominal group techniques, Delphi technique, checklists, and SWOT (strengths, weaknesses, opportunities, and threats) analysis (Ward and Chapman, 2003). Furthermore, the identification of uncertainties is also determined by expert judgment and experience (Maytorena et al., 2007).

NUSAP (Numeral, Spread, Assessment, and Pedigree) is a system of assessment (Funtowicz and Ravetz, 1990) which evaluates opinions and views rationally. It documents both the quantitative and qualitative dimensions of the problem under consideration and communicates them in a standard and explicit way. It systematically combines qualitative analysis and multi-criteria evaluation for a given knowledge base (Durugbo et al., 2010; Van Der Sluijs et al., 2005). The letter 'P' in the acronym NUSAP stands for 'Pedigree'. Pedigree assessment is a method for assessing the process of production of information. It involves a set of criteria assembled in a pedigree matrix. This matrix is used to evaluate a range of facets through qualitative expert judgment. It converts the qualitative judgments for each criterion to a discrete number scale. The criteria of judgment and the description of each level in the pedigree matrix can be tailored to suit the range of information in the project (Erkoyuncu et al., 2014; Goher et al., 2021a; Van Der Sluijs et al., 2005).

Analytical Hierarchy Process (AHP) is a multi-criteria decision-making methodology (MCDM) that helps the user assess the relative importance of mutually contradicting and subjective criteria (Ishizaka, 2019). It is an established technique that has received wide recognition amongst academic and industry practitioners (Ishizaka and Labib, 2011). In AHP there is a goal, a set of decision criteria, and a set of alternatives (Saaty, 2002). The decision-maker performs a pairwise comparison to opine about his or her preference by judging each of the criteria using relative ratio scales (Ishizaka and Labib, 2009) using the 9-point scale suggested by Saaty (Saaty, 1980). This leads to the formation of a comparison matrix followed by a weight vector which provides the percentage relative significance of each of the criteria (Goher et al., 2014).

The literature review indicates that little effort is made for a systematic and holistic investigation of uncertainties of model-based definition. There is a lack of any framework that solves the uncertainty management problem in the adoption of MBD. Moreover, no existing system is found that supports uncertainty management in the area of model-based definition and enterprise. To overcome these gaps a comprehensive uncertainty management system has been developed in this work. The developed system has taken into consideration all the aspects in the use of model-based definition across the product lifecycle.

## 3. Research methodology

This research was conducted over three years of study, and it was supported by two world-renowned aerospace industries within the UK. The data collection was conducted using techniques that included brainstorming, semi-structured interviews, focus group discussions, document sharing, and surveys. The interaction with the industry began in an iterative way which facilitated the identification, construction, and validation of the concepts during the study. The development of the framework was supported by twelve participants including academic and industrial subject matter experts. Fig. 1 presents the research activities undertaken for the development of the framework while the following lines describe them individually.

The identification of uncertainties was the most fundamental activity in the process of developing the framework for the management of uncertainties. This research posed many questions that aimed to capture various sources of uncertainties that arise in the path toward the model-based enterprise. A comprehensive literature review and initial interaction with the collaborators made it evident that there is a need to systematically capture the uncertainties for achieving the status of a model-based enterprise. Therefore, this research aimed first to establish a comprehensive list of uncertainties. Literature and interaction with collaborators were used to formulate an initial list of uncertainties comprising of 20 uncertainty factors. After this preliminary work, a methodological approach was adopted for finalising this list.

For this purpose, semi-structured, and structured interviews were conducted in order to fine-tune the definitions and concepts of the initially identified uncertainties in previous step. Furthermore, a survey was conducted to seek views of industry and academia on the validity of the identified uncertainties. The survey was based on the Likert scale seeking the respondent's level of agreement to the existence of each of the listed uncertainty. The survey also provided the opportunity to the respondents to add any uncertainty that is missing or overlooked in the initial list. The survey was conducted within and outside the collaborator organisations along with LinkedIn groups. The output of the survey was validation of the uncertainties with some of the additional uncertainties. It also helped rank the uncertainties, which were used later in the project for the selection of top-rated uncertainties for mitigation strategies. The survey and the interviews resulted in a refined list of uncertainties.

After formulation of the refined list, focus group discussions were conducted which were attended by experts from academia and collaborator organisations. These sessions focussed on further discussion on each of the uncertainty with its implications. This resulted in further refinement of the underlying concepts on each of the uncertainty. The result of this activity was an appropriately categorised final list of uncertainties of model-based definition.

A further activity conducted within these focus groups was to formulate mitigation strategies for highly ranked uncertainties. The ranking of uncertainties in the results of the survey was used to select the top five uncertainties. These uncertainties were thoroughly analysed in focus group meetings with the academia and collaborating industry, and a knowledgebase for mitigation strategies was developed. The final list of uncertainties of model-based definition and the developed mitigation strategies were made part of the uncertainty management framework which is described in the upcoming section.

In developing the framework, the second important activity was the selection of suitable methods for quantification and prioritisation of the uncertainties. Two methods were adopted for this purpose which are NUSAP pedigree assessment, and AHP. The pedigree assessment is used to record the level of uncertainty for each of the relevant uncertainty types. The rationale for adopting this method is its ability to reduce the arbitrariness and subjectivity of the judgment by transforming qualitative judgment into quantitative data and thus improving the quality of information. AHP is used to record the weight of uncertainty. This method was adopted due to its ability in facilitating judgment between various mutually conflicting uncertainty factors.

Finally, validation of the proposed framework and the system was done with the industrial experts. The criteria for validation were decided in a focus group workshop within digital manufacturing research group at Cranfield University. During this session the logic, comprehensiveness, generalisability, and practicality of the framework were agreed to be queried for the validation. This also included potential limitations and challenges in using the developed uncertainty management system.

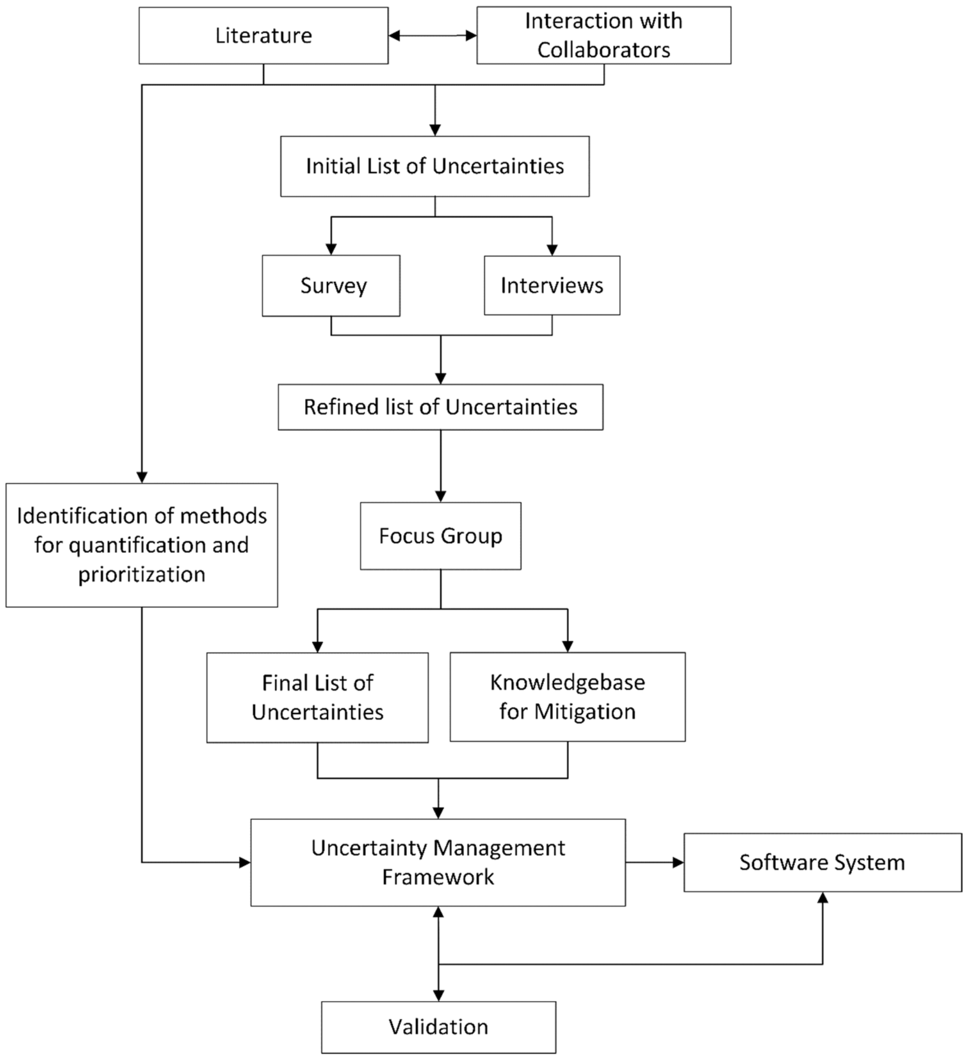



**Fig. 1.** Research methodology.

## 4. Developed framework

This study has combined theory and practice in applied research for proposing this framework for managing uncertainties in pursuit of the model-based enterprise. A systematic procedure was followed to outline the features of the framework.

The elements of the framework were developed primarily in the light of deeply studied literature and interaction with the academic and industrial experts. An extensive industrial input was sought to support the underlying concepts development, and validation of the framework. The best practice uncertainty management process can be broken down into five key stages which are planning, identification, analysis, response, and management. At first, the project manager needs to plan to define which activities should be considered to assess for the uncertainties. Additionally, he needs to pick the most significant areas for this assessment. Secondly, the identification stage enables the project manager to figure out uncertainties that may affect the objectives. Thirdly, by analysing qualitatively and quantitatively the project manager evaluates the likely consequences of the uncertainties. The qualitative process uses subjective judgments to prioritise the risk or uncertainty for action. Quantitative methods, on the other hand, impart higher confidence levels in the estimates and thus aid the decision-making on solid evidence. Fourthly, response planning concentrates to devise and implement activities to deal with high-priority risks or uncertainties. Finally, all the processes ascertain the importance of keeping the process alive and building the knowledge base for the future. All these five stages along with industrial interaction helped to formulate the overall structure of the proposed uncertainty management framework in this research.

Following the literature review and interviews, it was established that five phases would be incorporated into this framework named as preliminary phase, identify, assess, analyse, and respond phase. Fig. 2 presents the overall framework while the following section explains each of these phases.

### 4.1. Phase 1: preliminary phase

The first phase of the framework incorporates the following activities.

1. Define the scope of assessment

- Selection of the domain/s of product lifecycle for the assessment

2. Capture prerequisite information, including

- Functional requirements and objectives

The conventional product lifecycle comprises many stages including multiple domains like design, discrete part manufacturing, assembly,

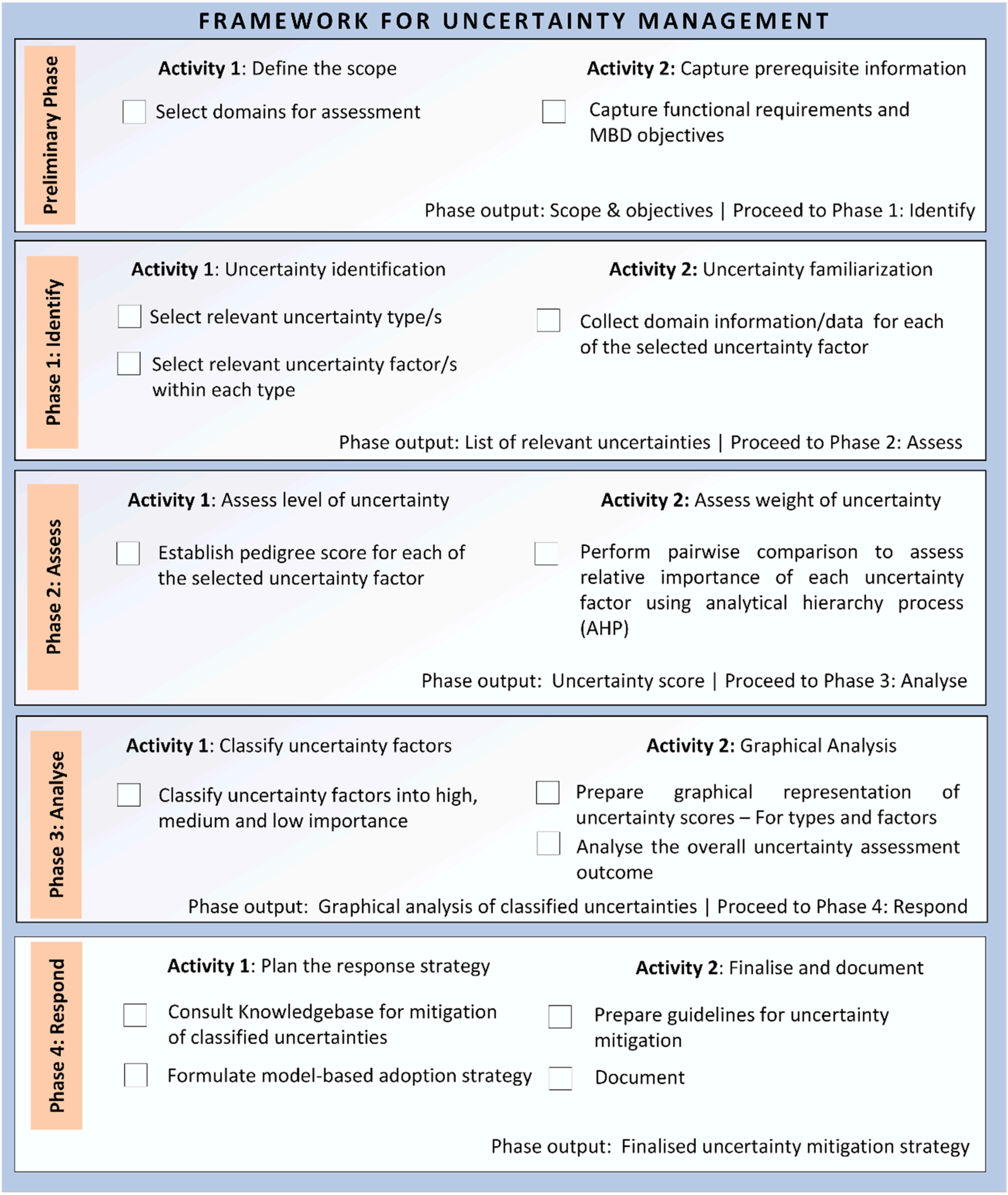



**Fig. 2.** Framework for uncertainty management.

inspection, maintenance, repair, and overhaul. Since this framework is designed to manage uncertainties for these domains individually as well as the enterprise as a whole, the first activity in this phase requires defining the scope of assessment and which domain/domains are needed to be assessed for the management of uncertainties. The second activity is to capture the specific information regarding the requirements of the domain concerning the model-based definition and the future objectives of the domain/domains for the adoption of the model-based definition.

A use case of applying the framework for assessing assembly stage for the adoption of MBD is considered. The functional requirements of this stage are needed to be thoroughly studied first such as the current form of assembly documentation, its process and time of creation, the issues with the current practices, and through adoption of MBD to-be scenario requirements, adoption challenges, and gaps to be filled.

### 4.2. Phase 2: identify

This is the second phase of the framework, and it comprises the following activities:

1. Uncertainty identification by:

- Selection of the relevant uncertainty type/s
- Selection of the relevant uncertainty factor/s

2. Uncertainty familiarisation by

- Collection of the domain information/data for each of the selected uncertainty types and factors.

The final list of uncertainties of model-based definition that have been determined during the initial stages of this research (Goher et al., 2021b) laid the foundation of this framework. This list is presented in Table 2. It comprises 31 uncertainty factors which are categorised into five types.

The identification activity within the framework aims to select the uncertainty type and factors that are most relevant to the domain under consideration or the organisation as a whole. The framework facilitates the selection of relevant uncertainties from the pre-defined list of uncertainties and thus provides an opportunity to tailor the list of uncertainties according to the need of the user.

The second activity within this phase is the collection of all the relevant information regarding the selected uncertainty types and factors. This is to ensure that the user of the framework could systematically assess these uncertainties on the ground of the best possible data related to the uncertainty under consideration. This will be input into the third phase.

Through considering the use case of assembly and the uncertainty factors of semantic PMI incorporation and consumption, one of the requirements in high-value manufacturing is the use of intelligent tooling in inspection and testing of assembly. The user needs to study what are the current practices of PMI incorporation and consumption. Additionally, it needs be further studied why and how much important it is to acquire semantic PMI capabilities in to-be scenario. Such type of information would lay the basis for selection of uncertainty type, its relevance and importance.

**Table 1**
Summary - key areas of literature.

| | Area | Authors |
|---|---|---|
| 1 | Product Definition, Traditional 2D Drawings – Use and Features | (Bijnens and Cheshire, 2019; Miller et al., 2017; Venne et al., 2010) |
| 2 | Model Based Definition – Use, Features and Benefits | (Bijnens and Cheshire, 2019; Quintana et al., 2010: Geng et al., 2014; Ruemler et al., 2017; Venne et al., 2010) |
| 3 | Evolution, Future, Challenges and Uncertainties of MBD | (Bijnens and Cheshire, 2019; Briggs et al., 2010; Hedberg et al., 2017; Miller et al., 2017; Quintana et al., 2010; Ruemler et al., 2017) |
| 4 | Role of Uncertainties in Technology Adoption | (Erkoyuncu et al., 2013; Goher et al., 2021b) |
| 5 | Risk and Uncertainty Management – Definition, Process, Role in Decision Making and Organisation Strategy | (Hubbard, 2010; Ward and Chapman, 2003; A guide to the project management body of knowledge, 2017) |
| 6 | Uncertainty Identification Methods | (Ward and Chapman, 2003; Maytorena et al., 2007) |
| 7 | NUSAP Pedigree Assessment | (Funtowicz and Ravetz, 1990; Durugbo et al., 2010; Van Der Sluijs et al., 2005; Goher et al., 2021a) |
| 8 | Analytical Hierarchy Process | (Ishizaka, 2019; Ishizaka and Labib, 2009, 2011; Saaty, 1980, 2002) |

**Table 2**
Finalised list of uncertainties.

| No | Uncertainty Type | Uncertainty Factor |
|---|---|---|
| 1 | Technological Readiness | • Software capabilities<br>• Semantic PMI incorporation capability<br>• Semantic PMI consumption capability<br>• Interoperability<br>• Hardware supporting MBD<br>• Low-cost hardware and software solutions for suppliers<br>• Standards<br>• Interpretation of standards and PMI application techniques |
| 2 | Managerial/ Implementation | • Legacy data<br>• Vendor lock-in<br>• Supplier readiness<br>• Supplier MBD capability assessment criteria<br>• Frameworks for evaluating the benefits of adoption of MBD at various stages of the product lifecycle<br>• MBD strategy<br>• Frameworks/criteria for software evaluation and selection<br>• Ability to handle product complexity<br>• Change management Strategies<br>• Training |
| 3 | Trustworthiness | • Privacy, Confidentiality, and Security of data<br>• Poor model quality<br>• Reliability<br>• Resilience |
| 4 | Certification | • Availability<br>• Accessibility<br>• Interpretability<br>• Integrity<br>• Quality<br>• Security |
| 5 | Affordability | • Supplier affordability<br>• Framework for cost-benefit analysis<br>• Organisation's affordability |

### 4.3. Phase 3: assess

This phase consists of two key activities.

1. Assessment of the level of uncertainty
2. Assessment of the weight of the uncertainty

This defines the quantification and prioritisation processes and leads to the "uncertainty score", which represents the numerical value of the impact of uncertainty on the project. This score is derived by multiplying "uncertainty level" and "uncertainty weight".

***Uncertainty level:*** For assessing the level of uncertainty, the pedigree assessment process was adopted as described in Section 3. Three criteria have been set for the pedigree assessment. Each criterion and its description for various levels are tailored to suit this research. The first criterion is the 'basis of estimate' which represents the availability of the relevant data and the expert's level of expertise in the area. 'Rigour in assessment' evaluates the methods that are used for the collection and analysis of the data for assessment. 'Level of validation' evaluates the degree of effort made for verification of the available data against independent resources. A scale with values 1, 3, 5, and 7, is used for this assessment. The higher the value the greater is its severity hence the higher is the level of uncertainty. The description of each criterion and the allocated score is presented in Table 3.

For every uncertainty, the expert needs to assess the credibility of his or her knowledge and accordingly assign the score. For the use case of

**Table 3**
Pedigree Matrix.

| Score | Basis of Judgement | Rigour in Assessment | Level of Validation |
|---|---|---|---|
| 1 | Best possible data, Large sample of data, Use of historical data | Best available practice in a well-established discipline | Best available, independent validation within the domain, full coverage of processes |
| 3 | Some experience in the area, Small sample of historical data, Internally verified data | Sufficiently experienced and benchmarked internal process with consensus on results | Internally validated with sufficient coverage of processes and verified data, Limited independent validation |
| 5 | An educated guess, Indirect approximation, Rule of thumb estimate | Limited experience of process with a lack of consensus on results | Limited internal validation, No independent validation |
| 7 | No experience in the area, Speculation | No discernable rigour | No validation |

assembly, the preliminary studies at phase 1 and 2 and the knowledge of the expert along with the data on which he is making the assessment will lay the basis of this judgement. The average of the assessed scores for all three criteria defines the level of uncertainty. This score is used in the prioritisation and quantification process of the uncertainties in combination with the “uncertainty weight” which is being described in the following sections.

***Uncertainty Weight:*** The uncertainty weight represents the significance of an uncertainty factor when compared with other uncertainties under consideration. This weight is obtained using the analytic hierarchy process (AHP) performing pairwise comparison of all the selected uncertainties.

The product of the level of uncertainty and weight of uncertainty gives the resultant overall significance of the uncertainty factors under consideration which is termed as “uncertainty score”. This process is shown in Fig. 3.

### 4.4. Phase 4: analyse

In this phase, the framework proposes a classification of the uncertainty factors based on the uncertainty score calculated in the previous phase. This is followed by the distribution of the uncertainty factors with respect to their severity which may be high, medium, and low. The following lines describe the method that was used to set the range values of the scores for these three classes.

Since in this framework the number of selected uncertainty factors vary within each of the uncertainty types, the range value for high, medium, and low severity uncertainties are also variable. This is

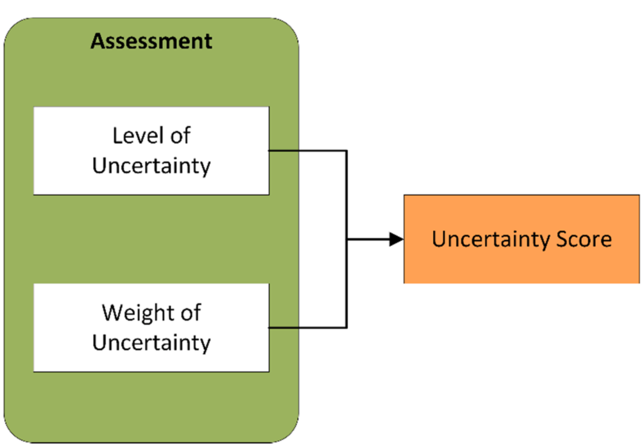



**Fig. 3.** Assessment process.

calculated based on the number of uncertainty factors selected. The formulae for this calculation are as under.

$$If:$$

$$Number\ \ of\ \ uncertainty\ \ factors\ \ selected\ \ in\ \ an\ \ uncertainty\ \ type\ \ x = N_{ufx}$$

$$Mean\ \ Pedigree\ \ Score\ \ (Constant) = \frac{1+3+5+7}{4} = 4$$

$$Mean\ \ of\ \ the\ \ uncertainty\ \ scores\ \ for\ \ N_{ufx}\ \ uncertainty\ \ factors = M_{ufx}$$

$$Then:$$

$$M_{ufx} = \frac{1}{N_{ufx}} \times Mean\ \ Pedigree\ \ Score$$

$$And, the\ \ ranges\ \ for\ \ calssificaion\ \ would\ \ be:$$

$$High\ \ Severity\ \ Score\ \ Range = 0.66 \times 2M_{ufx} - 2M_{ufx}$$

$$Medium\ \ Severity\ \ Score\ \ Range = 0.33 \times 2M_{ufx} - 0.66 \times 2M_{ufx}$$

$$Low\ \ Severity\ \ Score\ \ Range = 0 - 0.33 \times 2M_{ufx}$$

The second activity within this phase is the presentation of the assessment results in graphical form. For this analysis two charts are proposed:

1. Spider Charts – For analysis of the scores of the five uncertainty types.
2. Horizontal Bar Charts – For visualisation of the uncertainty score of each of the uncertainty factors within a particular uncertainty type.

In this way, two forms of analysis are proposed.

1. Classification of all the assessed uncertainty factors into high, medium, and low severity.
2. Graphical analysis of selected uncertainty type and uncertainty factors.

### 4.5. Phase 5: respond

This is the last phase of the framework which includes the following set of activities.

1. Plan the response strategy through:

- Consulting the knowledgebase, and
- Formulating the model-based definition adoption strategy

2. Finalisation of the MBE strategy through:

- Preparation of the guidelines for uncertainty mitigation, and
- Documenting

For this purpose, a knowledgebase is incorporated within the framework. Though identifying mitigation for each of the identified uncertainty is important and needs detailed work, due to the time limitation of this research, this work has focussed only on the key uncertainties to develop the mitigation knowledgebase. Therefore, the top five of the most important uncertainties which were obtained in the result of the survey were selected. These five uncertainty factors are:

a) Framework for cost-benefit analysis
b) Legacy data

c) MBE strategy
d) Training
e) Model quality

A workshop (2-hour long) was held with the collaborators for formulating the mitigation strategies. The top five key uncertainties were presented before the participants and recommendation of the participants was sought for suitable mitigation strategies. While discussing each of the uncertainty, the following are the questions that were asked by the participants.

i. What should be the key elements of the mitigation strategies for the uncertainty under consideration?
ii. What should be the key steps to follow while mitigating the uncertainty?

In the following lines, the results of the workshop are summarized for each of the top five uncertainties.

#### 4.5.1. Framework for cost-benefit analysis

- *A standardized approach to capture the data for business case:* Though demonstrating ROI (return on investment) for investment in technology to various stakeholders is quite common in the industry, in the case of MBD the benefits are already known and proven. However, it is important to develop a mechanism for capturing the data from the business which will help to tailor the business case. This could be challenging; therefore, a standardized approach must be adopted for this purpose.
- *Consideration of the business case as a whole:* It is important to consider the business case for MBD as a whole instead of seeing and analysing it for a particular domain. People currently see only the design perspective and miss the significant impact on manufacturing, quality, and other downstream domains concerning the ability of the MBD to efficiently consume the MBD data. Similarly, some organisations are keeping the emphasis on manufacturing only and not considering the other domains. MBD will be more beneficial by considering a lifecycle approach. Integration of all MBD in the existing manufacturing execution system (MES) will help in this regard.

#### 4.5.2. Legacy data

There are three approaches found to deal with legacy data from the perspective of the adoption of model-based definition. These are described below.

i. There is no need for legacy data shift to MBD at all: The reasons in support of this approach are as under.

- It will be expensive. Re-mastering will not be a financial saving.
- Since most 3D models produced today are still converted to existing drawing formats so there is no question of the legacy conversion.
- Re-mastering will be needing revalidating and in line with the MES. That will add to the troubles and complexities. It will rather be a bigger problem than actually the re-mastering process itself.
- The time and effort to do this is huge.

i. *A selective approach for the shift:* The reasons in support of this approach are as under.

- It doesn't make sense to convert them all.
- There must be some specific reason or a business case for re-mastering. Some companies have done re-mastering effectively for a limited number of cases for a specific reason i.e., automating the measurement process. A selective approach, therefore, can be adopted for the conversion of legacy data from conventional drawing to MBD which must be based on strong grounds.

i. Eventually, the organisations will need this shift: The reasons in support of this approach are as under.

- Older systems can not last forever. Legacy has to be eventually converted into new formats.
- Automating the workflow is available with the MBD but not available with the conventional drawings.
- If legacy data is not converted there would be many challenges in working practices and processes. It will become quite difficult to keep both conventional formats for legacy and MBD for new products in parallel.
- In remastering data, although the cost is high but if we use that data regularly for operational use then it is worth investing in it. Even marginal benefits are worth spending as the re-use of data is phenomenal.
- Another factor is the new workforce that is 3D-based.
- Legacy is important. In the MBD lifecycle, the data should flow both ways. This will be a two-way process that involves a lot of learning. In case we do not shift, what the legacy data has to offer for this learning so that the design process may be informed.

#### 4.5.3. MBE Strategy

- *Elimination of silo:* An appropriate strategy must be tailored to avoid the silo. Normally engineering teams in various domains evolve more in a silo at the moment. For a comprehensive MBD strategy, it is needed to set up the actions for all engineering functions which enable them to avoid this phenomenon.
- *Making people understand*: The following elements must be very clear within the people's minds: what we are doing for MBE? why are we doing it? and what would be each individual's role in the MBE processes? One way of doing this is to establish focus groups.
- *Awareness across the organisation:* The MBE strategy must ensure awareness of people with a cross-boundary approach. All organisations must understand MBE and its role.
- *Other elements of the MBD strategy:* It must include people, cultural change, technology, tools, and standards.

#### 4.5.4. Training

- *Mindset shift:* People need to understand how they are implementing MBD in their design space. They must know that they are not designing only a component but designing it for the assembly and other purposes as well. A convergence of engineering and manufacturing is quite essential, therefore.
- *Improvement in digital skillset:* The training must include improving the capability of using digital tools.
- *People awareness element:* The way of designing has to be changed. It is needed to make people aware that what they are dealing with. Therefore, a whole new way of thinking is required. For this objective, a holistic MBD training would include understanding this change, culture, and systems.

#### 4.5.5. Model quality

It is closely related to the awareness of the designer. People working on the model should know why they are doing it.

## 5. Software system for uncertainty management

Following the development of the framework, a software system is created to support the framework for uncertainty management. This is done to facilitate the framework users in the accomplishment of the defined activities within the framework. The system facilitates the analyst to select the relevant uncertainties from a defined list, systematically assess and analyse each of the uncertainty and obtain recommendations for mitigation of the prioritised uncertainties in the project. This section describes the architecture of the developed system, its functions, and the system scenario including the key features, inputs, and outputs.

### 5.1. System development

The uncertainty management system developed to support the proposed framework consists of a user interface, a database of uncertainties, an assessment module, an analysis and prioritisation module, and a knowledge base of mitigation strategies. The overall architecture of the system is presented in Fig. 4.

### 5.2. System architecture

A user interface has been developed to provide an environment that must be easy to understand and manipulate. It must also be designed in such a way that operating the system itself is not much complicated such that it may facilitate and support the user to concentrate on the actual analysis. These features are taken care of while developing the interface.

The uncertainty database within the system is composed of the identified uncertainty types and uncertainty factors. This database sets the baseline for using the assessment module. This database is static, which means it will not be altered during the system usage unless an upgrade to the system is done.

The assessment module incorporates the uncertainty assessment methodologies. This module facilitates the user to apply pedigree assessment and AHP techniques. The user options and the fields in this module are designed such that only the information input is visible to the user while all the complex matrices of AHP run in the background. This is done to free the user to face any complex calculations, as, the users of such systems are mostly interested in the outputs of the system.

The analysis and prioritisation module equip the system with the logic and rules that have been developed to classify the assessed uncertainties. It also provides the analysis features by converting the outputs into visually understandable graphic output. Finally, another static database, that incorporates the mitigation strategies, is developed within this system. This database provides the source for relating the assessed uncertainties with the corresponding mitigation strategies.

Two types of data are generated while using the system namely project uncertainty analysis and key uncertainty mitigation. The former is populated with the analysis of the assessed uncertainties of the project while the latter is populated by the mitigation strategies of the prioritised uncertainties. Both of these data types are temporary, and the system clears them on reset. However, the PDF report generation features have been incorporated within the system to record the session outputs for future reference.

### 5.3. System scenario

The system scenario describes the activities that are needed to performed by the user while using the developed software system. It is

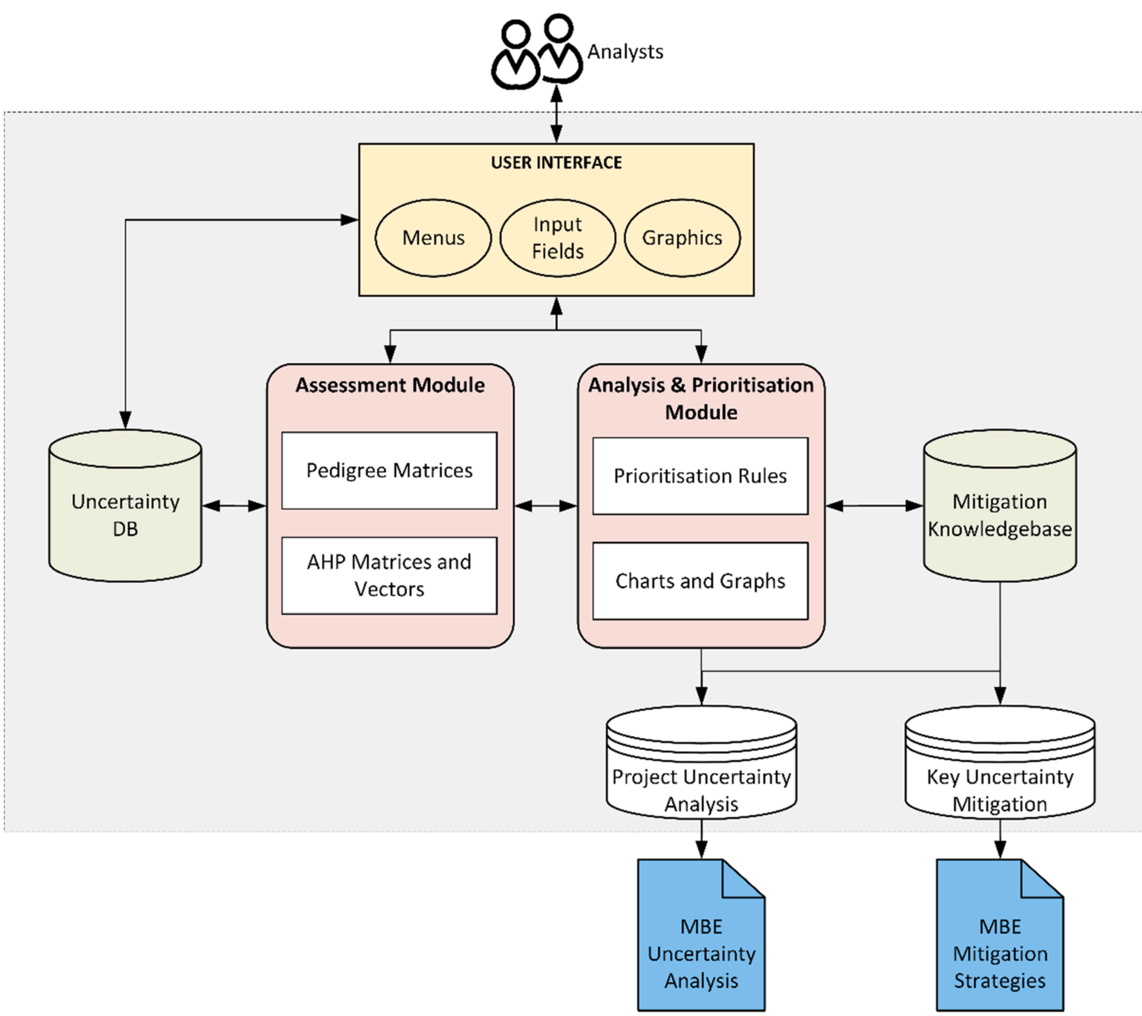



**Fig. 4.** System architecture.

represented through an activity flow chart in Fig. 5.

The flow of the activities involves first defining the scope of the project. This may include analysing either a single domain such as design, manufacturing, assembly, etc., or multiple domains under consideration. The next activity before using the system is capturing the domain information. The user must collect necessary information about the domain/domains under analysis including the present state and the future objectives of the domain related to its functioning within a model-based enterprise. Where possible the captured information must be documented and validated, else the uncertainties under consideration shall be a higher impact later in the results. The next activity is to select the relevant uncertainty types and uncertainty factors from the menus that have been provided within the developed software system. These features of the system allow the analyst to optimize the uncertainty list according to its relevance with the domain/domains under study.

This is followed by the most important activity to be performed by the analyst. The first sub-activity within this activity is the allocation of pedigree assessment scores to each of the selected uncertainty. This requires a fair analysis of the data the analyst had captured and consequently performs the scoring process. The second sub-activity is to perform the pairwise comparison between all the selected uncertainties using the AHP approach. The system has eased this process by incorporating a drop-down menu with a score and its description. The system itself computes all the remaining processes of pedigree assessment and AHP described in the methodology section. The screenshots of the system while performing these processes are presented in Figs. 6 and 7. This results in reaching an uncertainty score for each of the uncertainty.

Afterward, the system performs the prioritisation process by applying the rules set for this purpose and described on Section 4.4. This results in the classification of uncertainties with respect to severity i.e., high, medium, and low values and is displayed using color-coding which are red, orange, and green respectively. The output is displayed in tables as well as charts and graphs to facilitate the analysis as represented in Figs. 8 and 9.

The next activity is the selection of appropriate mitigation strategies for the prioritised uncertainties. This is aided through the knowledge base of mitigation strategies developed within the software system. Finally, the system generates uncertainty analysis and mitigation reports.

## 6. Validation

The validation presents the results of semi-structured interviews that were conducted to check various aspects of the developed uncertainty management framework and the corresponding software system. These aspects include usability, generalisability, benefits, limitations, and areas to improve. During these validations, the approaches of developing the framework and the system were queried. In doing this a holistic approach was adopted covering as many aspects as possible. The respondents were also provided sufficient time to opine beyond the fixed questions. To conduct these validations, 6 interviews were conducted with experts having 10–44 years of experience and currently having leading roles in the areas of design, manufacturing, digital manufacturing technologies, PLM systems, SCRUM techniques, and design process architecture.

The framework overall was observed to be detailed, well-structured, and well-elaborated along with the process of uncertainty management in the framework to be valid and easy to understand. The list and categories of uncertainties were found comprehensive and fine-tuned by all of the respondents. The approach of using AHP to assess weight and pedigree matrix to assess the level of uncertainty along with the method of calculation of resultant score was found self-explanatory and detailed.

The framework was found suitable for various domains of the aerospace industry such as design, manufacturing, assembly and test, maintenance, repair and overhaul (MRO), and information technology (IT) by all the respondents. Whilst, in the context of generalisability, the framework was found to be generalisable for the aerospace industry as well as other industry sectors, since the normal product development process is fairly similar across all the industries. Furthermore, the framework was found equally suitable to be used by the organisation itself, the suppliers, and the solution providers. Table 4 presents the average score by each of the experts for the aspects that needed quantitative input. The higher the score, the higher is the expert's level of agreement to the validity of the framework for the criteria under discussion. It can be seen that majority of the criteria were scored 9.0 or above which indicates a high level of agreement for the validation of the framework.

The framework and the system were found to greatly benefit an organisation as a whole as well as individual domains to see and assess the key uncertainties in the process of adoption of model-based definition. In one of the respondent's views, this work presents very clearly what has been done before and puts forth the key points the practitioners need to look at. In this way, it avoids the things to be reinvented. The use of this framework can help the industry interpret the identified uncertainties and then can validate them against each other. In another respondent's view, the system provides a very systematic method that gives proper validation of the work when a team has to go for financial support for its project. It provides a rational way to show that a proper assessment has been done before doing what the project is looking at. It approves that the team working on the project has looked at all the problems and presented them to the management by using the conclusion, the priorities, and the ways how the organisation needs to tackle them. Overall, the system was found to be very good and professional. The respondents further added that normally we present our material and people say: well, it is just what you think. But if we use a supporting system like this, we can present it to the senior management in a better way. Finally, the knowledge base provided in the system to mitigate the uncertainties was also found to be suitable and beneficial. It was supposed to provide a very good baseline for MBE strategies.

## 7. Discussion and industrial implication

MBD is the heart of digital transformation for product data and a key enabler of smart factory and industry 4.0. The manufacturing industry in general and high-value manufacturing, in particular, is adopting MBD at a very fast pace. However, the uncertainties in the process of this adoption are hindrances to the realisation of complete model-based enterprise and are needed to be systematically worked upon. It is imperative, therefore, to thoroughly study and analyse various aspects of MBD/E for the risks and uncertainties and apply this knowledge by using a methodological approach to benefit the decision-making process for formulating effective adoption strategies.

This paper has provided an innovative approach for management of the uncertainties in adoption of model-based definition throughout product lifecycle by proposing a framework. An in-depth study was carried out first to determine 31 key uncertainty factors of MBD which were further categorised into five types. Using the identified uncertainties as a baseline, NUSAP pedigree and analytical hierarchy process (AHP) were used for assessment and prioritisation processes within the developed framework. The pedigree assessment facilitates enhanced credibility of the analysis through scoring the quality of the judgment and thus provides a purifying method for any judgment. AHP is a proven technique for assessing the relative significance of various mutually conflicting criteria for decision analysis. It enables the comparison of various criteria by offering a pairwise approach and at the same time transforming the qualitative assessment into quantitative data. A knowledgebase for mitigation strategies of key uncertainty factors was provided within the framework and a supporting IT system was developed to facilitate the application of framework.

This framework will provide a platform for the industry to get in-depth knowledge of the uncertainties involved in the process of adoption of the model-based definition, assess them rationally and

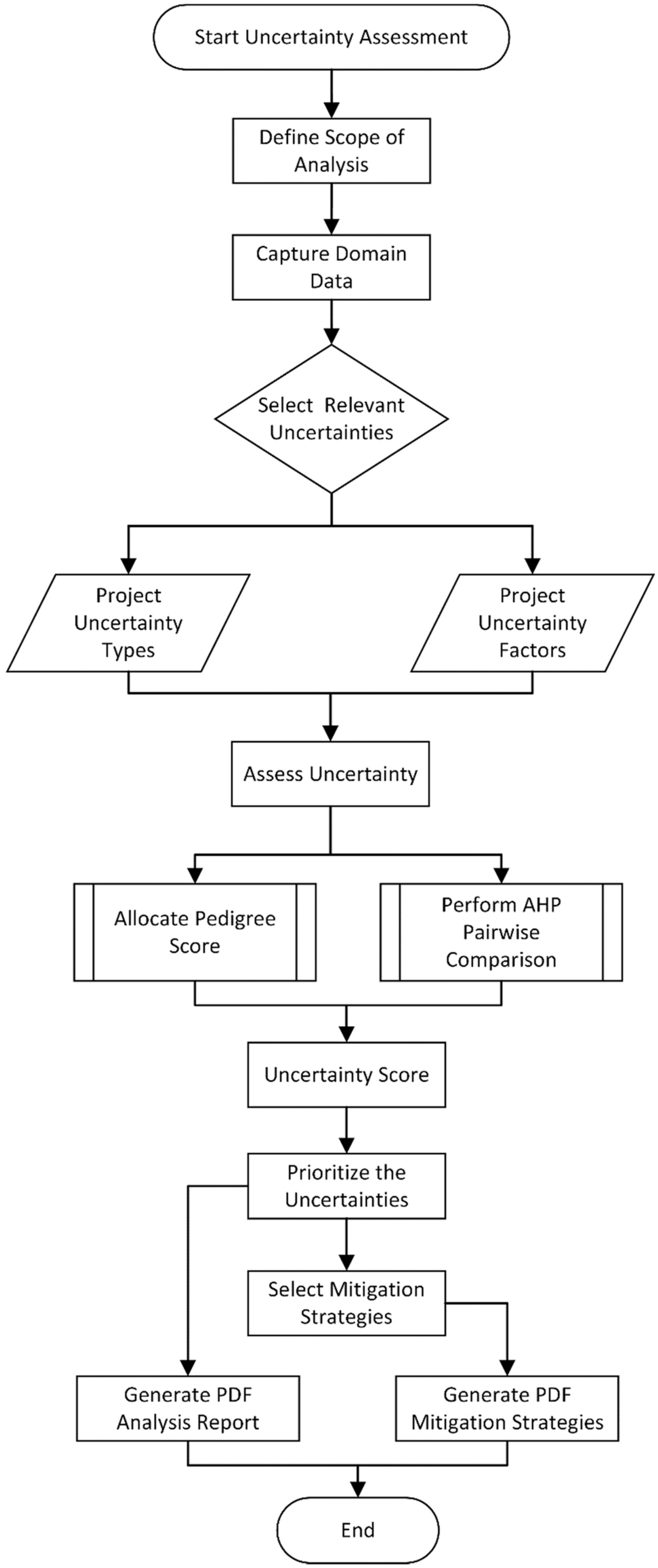
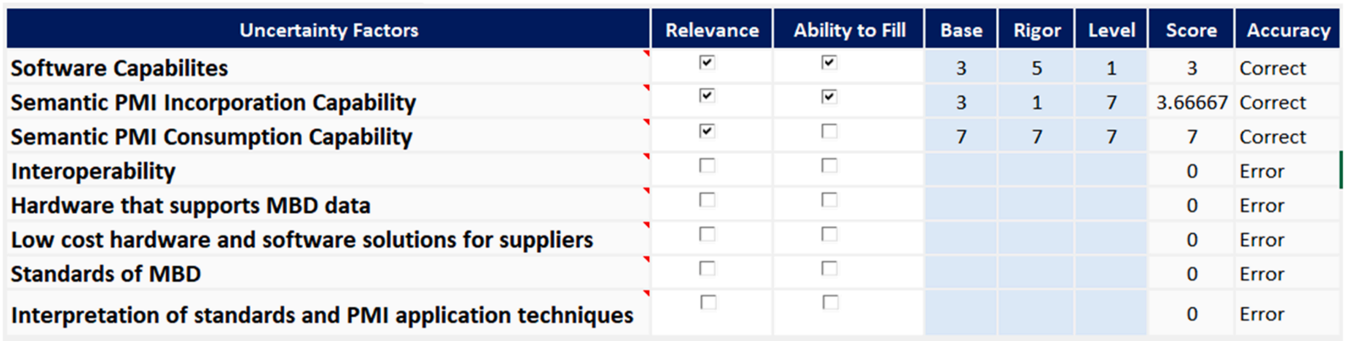



**Fig. 5.** System scenario.



| Uncertainty Factors | Relevance | Ability to Fill | Base | Rigor | Level | Score | Accuracy |
|---|---|---|---|---|---|---|---|
| Software Capabilites | ☑ | ☑ | 3 | 5 | 1 | 3 | Correct |
| Semantic PMI Incorporation Capability | ☑ | ☑ | 3 | 1 | 7 | 3.66667 | Correct |
| Semantic PMI Consumption Capability | ☑ | ☐ | 7 | 7 | 7 | 7 | Correct |
| Interoperability | ☐ | ☐ | | | | 0 | Error |
| Hardware that supports MBD data | ☐ | ☐ | | | | 0 | Error |
| Low cost hardware and software solutions for suppliers | ☐ | ☐ | | | | 0 | Error |
| Standards of MBD | ☐ | ☐ | | | | 0 | Error |
| Interpretation of standards and PMI application techniques | ☐ | ☐ | | | | 0 | Error |

**Fig. 6.** Pedigree assessment.

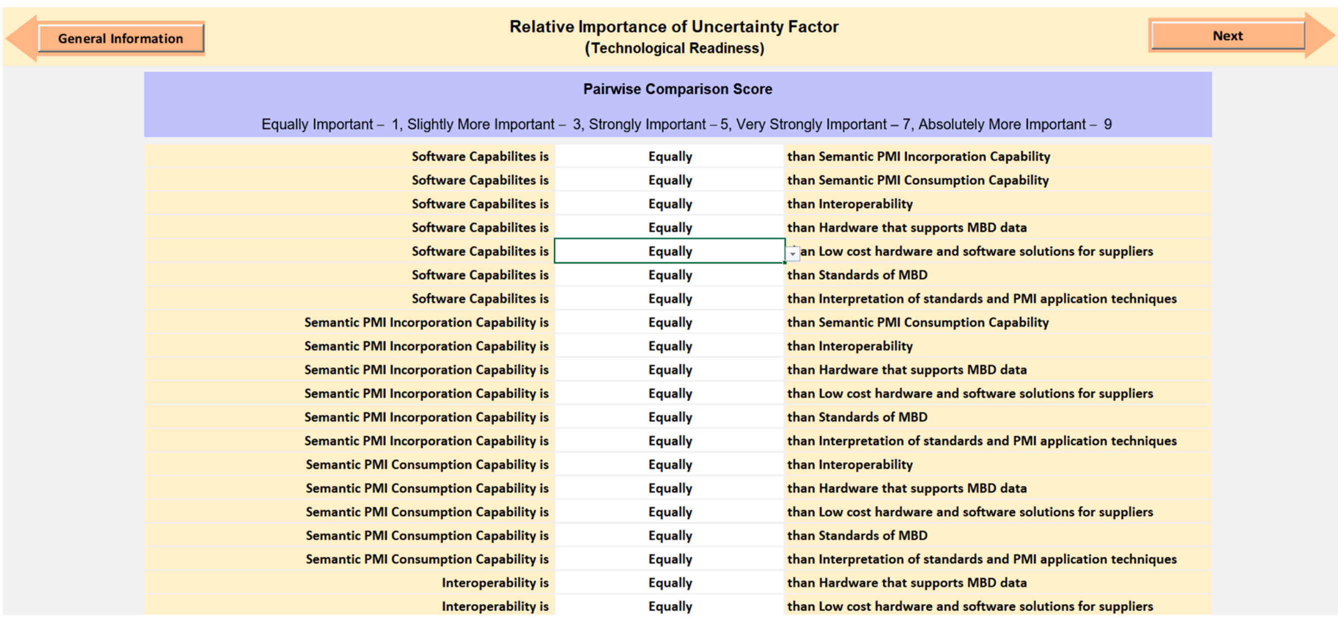



**Fig. 7.** AHP pairwise comparison.

subsequently formulate a practical model-based enterprise (MBE) strategy. The supporting software system will facilitate industry and practitioners to apply the proposed framework and set the organisational strategy in an easy, understandable, and organised way. The outputs of the system may further be uses as a baseline for industry to communicate their core issues to software solution providers and thus reduce the solution development times.

### *7.1. Implications for the industry*

The discussions with various industrial and academic experts during development and validation of this work implies that the proposed uncertainty management framework will enhance the quality of decision-making in formulating model-based enterprise strategy. It will provide an opportunity to see and analyse all aspects in detail, ensuring nothing is overlooked in the process of decision making.

The analysis results and solutions obtained while using the proposed system will have a huge significance. It is believed that understanding and learning from the attained results would be the key in getting value from the system. It would be imperative for the organisations using the system to stay engaged with those results and potential solutions in moving forward.

Another very important aspect would be getting the right input for the system from the right people. The individual user or the team using the proposed system must have some prior background knowledge of the processes, issues, and key problems of all the domains which are considered for adoption of MBD. The individuals must also know the current capabilities of the organisation and the overall status of the model-based definition within the organisation. As an alternative, the developed system may be used to analyse individual domains separately, and then the results may be aggregated to get the overall output. In this aspect, the system architects have a view of all the issues that are raised within the organisation and the offered solutions from the software vendors. While the maintenance of the system may be carried out by the team formulating the MBE strategy for a periodic reconsideration of prevailing uncertainties and a regular update and necessary adjustments in the strategies.

One of the limitations in the use of the framework is the rapid change in some of the uncertainties i.e., technological readiness. Since the technology is advancing a at a very quick pace the uncertainties may change in a quick time, hence, there must be regular update in the identified list of uncertainties through industry academia linkage.

## 8. Conclusions and future work

The uncertainty management framework presented in this article offers a process that enables the assessment of the influence of uncertainties on the adoption of model-based definition. A major contribution of this article is the identification of uncertainties encompassing the key factors that could affect model-based enterprise adoption

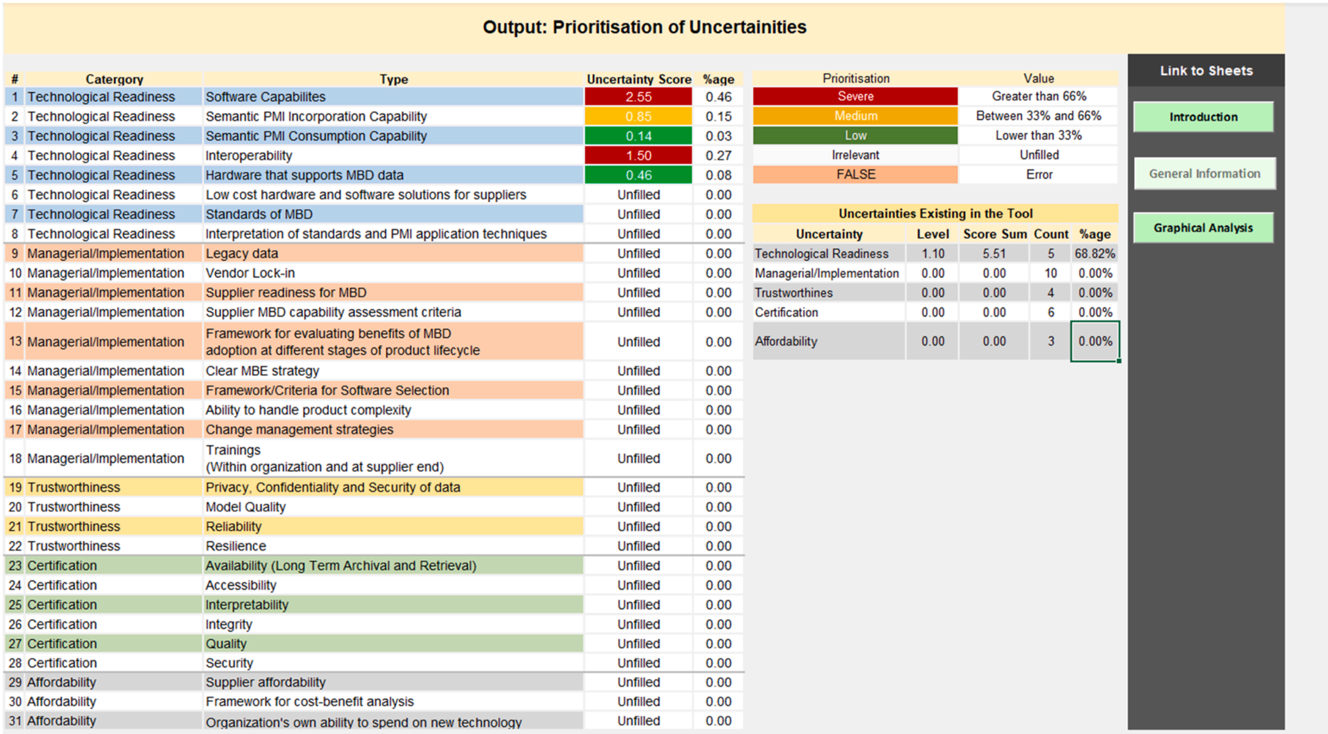



**Fig. 8.** Level of severity of uncertainties.

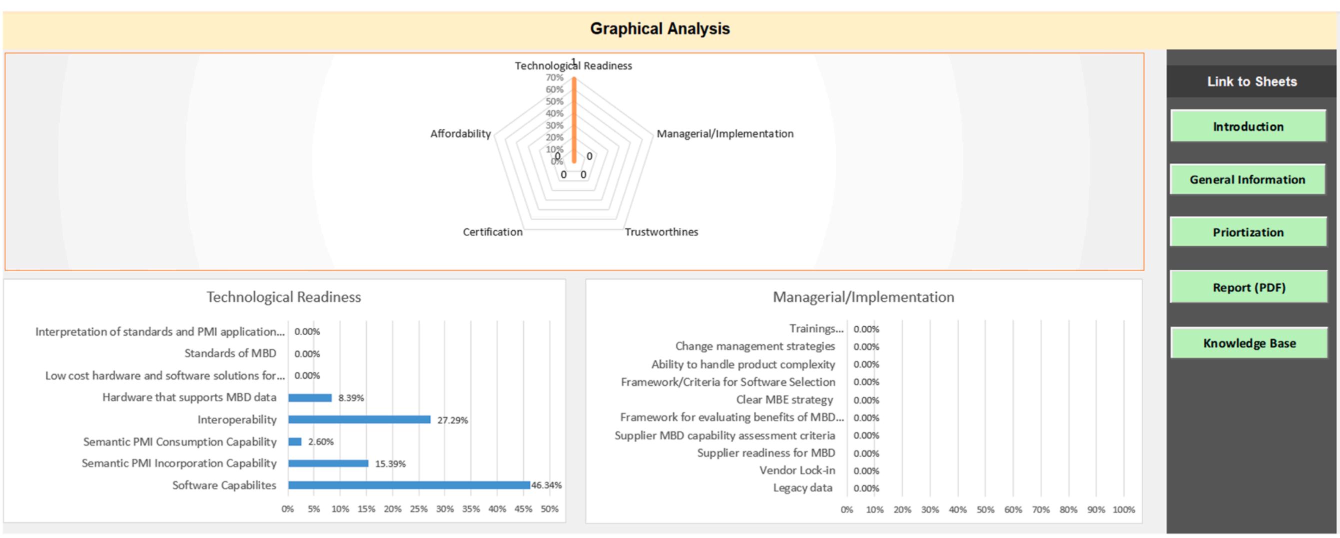



**Fig. 9.** Graphical analysis.

**Table 4**
Validation scores.

| Assessment Criteria | Score out of 10 (Average) |
|---|---|
| Logic | 8.0 |
| Suitability | 8.3 |
| Generalisability for aerospace | 9.8 |
| Generalisability for other industries | 9.0 |
| List and categories of uncertainties | 9.3 |
| Method of calculating the level of uncertainty | 9.3 |
| Method of calculating the weight of uncertainty | 9.3 |
| Calculation of uncertainty score | 9.3 |
| Mitigation knowledgebase | 9.0 |

strategy. The framework provides a novel approach to systematically identify, quantify, prioritise and analyse the uncertainties. It incorporates an exhaustive list of mitigation strategies to reduce, control or eliminate uncertainty. Another major feature of this work is the provision of novel guidance in the process of identification and prioritisation of uncertainties. In general, the framework offers an opportunity to manage the uncertainties in the path toward the model-based enterprise. A combination of pedigree assessment and analytical hierarchy process is used to develop the framework and applied in the developed system to deal with the uncertainties in the adoption of model-based definition. A user-friendly IT system consisting of menus, buttons, and graphics is developed in support of the framework for providing the analyst ease to input data to the systems and perform the analysis based on the processes in the framework. This work is part of research which will address to develop a framework for model-based definition for high value manufacturing products. Following are some of the future research directions in continuation of this work.

- The list of uncertainties would change with time due to the quick pace of technology advancements, which arise the need for periodic updates to this list by academia-industry collaboration.
- The knowledgebase for mitigation of uncertainties, in this research, presents only the strategies for highly ranked uncertainties due to the limitations of this work. Since technology is advancing very fast and the context of the industry also varies, completing and updating this knowledgebase for all the identified and future uncertainties could be of profound interest to future researchers.
- The methodology of the uncertainty management process in the framework can be improved by introducing other methods of decision analysis.

## CRediT authorship contribution statement

**Kamran Goher:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing – original draft. **Ahmed Al-Ashaab:** Supervision, Resources. **Shoaib Sarfraz:** Visualization, Writing – review & editing. **Essam Shehab:** Conceptualization, Supervision, Project administration, Funding acquisition.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data Availability

The data that has been used is confidential.

## Acknowledgments

The authors thank Higher Education Commission (HEC), Pakistan, and Cranfield University, the United Kingdom for funding this research. The authors also acknowledge the extensive collaboration support by Rolls-Royce and Airbus during various phases of this research.

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2023-05-30

# An uncertainty management framework to support model-based definition and enterprise

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Elsevier

Goher K, Al-Ashaab A, Sarfraz S, Shehab E. (2023) An uncertainty management framework to support model-based definition and enterprise, Computers in Industry, Volume 150, September 2023, Article number 103944

https://doi.org/10.1016/j.compind.2023.103944