Group Decision Support for Product Lifecycle Management

Abstract

Product Lifecycle Management (PLM) systems support industrial organizations in managing their product portfolios and related data across all phases of the product lifecycle. PLM seeks to enhance an organization's ability to manage its product development activities and facilitate collaboration across organizational functions and between organizations. Effective decision-making is vital for the successful management of products over their lifecycle. However, PLM decision-making is an under-researched area. We argue that decision-making theory and group decision support concepts can be brought to bear to enhance PLM decision-making processes. We present and justify a set of six principles to support decision-making in a PLM context. The paper highlights the need to consider and capture decisions as distinct units of PLM knowledge to support product lifecycle management. We derive a generic information flow and a group decision support structure for PLM decision-making that encapsulates the six principles. Three industrial cases are analyzed to illustrate the application and value of the principles in supporting decision-making. The principles enable PLM decisions to be codified, recorded, and reviewed. Decision-making processes can be reused where appropriate. The principles can support future innovations that may affect PLM, such as ontological and semantic reasoning and Artificial Intelligence.

1. Introduction

Product Lifecycle Management (PLM) systems have been developed over the last two decades to enhance an organization's ability to manage its product portfolios over the product lifecycle (Stark 2018). Such systems not only store data and information about products and the processes needed to produce them, but also seek to capture and reuse knowledge to support organizations in developing new products, manufacturing them, introducing them to the market, and managing them over their lifecycle (Enríquez et al. 2018; Marra et al. 2018). New products that enter the market go through growth, maturity, and decline phases until they are withdrawn or replaced (Saaksvuori and Immonen 2008; Corallo et al. 2013; Stark 2018). There may be significant levels of development, modification, and refinement in products and the processes by which they are produced over the product lifecycle. PLM systems seek to capture such data and information and allow it to be reused where appropriate.

PLM recognizes that information may be generated at any point in a product's lifecycle and may also need to be retrieved at any point in a product's lifecycle. Such data and information may be used by a diverse range of organizational functions (Stark 2018), including technical functions considering design and engineering issues related to products and processes, the quality management function monitoring product and process performance, and business functions such as finance considering product costing, and the marketing function examining new product launches. However, the provision of information alone is not enough to accomplish the enhanced support promised by PLM systems. The decisions that arise, and the decision-making processes that are necessary over a product's lifecycle must also be supported to enable an organization to manage its product portfolio However, decision-making in PLM is under-researched (Eigner et al. 2011). PLM review papers such as Meier et al. (2017) and Nyffenegger, Rivest and Braesch (2016) and practitioner literature such as Fleming et al. (2017) do not show evidence of specific support for decision-making in PLM.

The range and diversity of PLM decisions occurring across the product lifecycle are influenced by the industrial and business context (Stark 2018). However, typical types of decisions occur across different contexts over the course of the product lifecycle (Ameri and Dutta 2005). These include design and project progression decisions in stage-gated new product design processes (Eigner et al. 2011; David and Rowe 2016) and decisions around the timing of new product introduction (Spanjol et al. 2011). PLM decisions arise from product monitoring in the field (Kiritsis 2011), including design changes and modifications (Ameri and Dutta 2005), which may be performance, quality or service related (Kiritsis 2011; Cenamor et al. 2017). Decisions may relate to product maintenance and repair (Lee et al. 2008; Cenamor et al. 2017) as well as product retirement (Spitzley et al. 2005), and end-of life recycling, disposal or reuse (Kiritsis 2011). Product recall decisions are also critical for many products that have safety critical features (Mukherjee and Sinha 2018). Largescale recalls have been necessary for medical devices (Ball, Shah and Donohue 2018; Horton 2012; Sedrakyan et al. 2016) and for vehicles manufactured by major global producers (Bennett 2014; Calia 2014; Matthews and Lublin 2014; Smithers 2016). Such product recall cases highlight not only that organizations may need to retrieve data and information on product-related issues at any point in the product lifecycle but that, crucially, they also need to be able to retrieve and examine previous decisions made about products, their design, the processes used to make them, their performance and quality. The recent scandal

around the Volkswagen emissions testing defeat device raised questions on critical decisions made in the past (Parloff 2018).

PLM decision-making occurs within an organizational context and usually requires inputs from multi-disciplinary teams (Xu et al. 2007). Decision problems that arise within organizations rarely occur in the crisp, well-defined forms considered in classical decision theory (Klein et al. 1993; Beach and Lipshitz 2017). Typically, organizational decision problems require problem exploration, understanding, and clarification and may involve consensus building to arrive at an agreed course of action (Roy 1996; Zack 2007). For product and process related decisions, different organizational functions frequently need to collaborate (Tripathy and Eppinger 2011). In this work, we argue that group decision support concepts (DeSanctis et al. 2008) can be used to enhance PLM decision-making processes and can assist in defining the processes needed for information gathering, decision structuring, communication, and the recording of planned actions across the product lifecycle. We identify six group decision support principles applicable to PLM decisions from the literature on PLM, decision-making, and group decision support systems, which we illustrate and evaluate with three case studies. The six principles facilitate and enhance the recording of decision processes, enabling later examination and auditing of decisions and reuse of the decision process where appropriate.

In Section 2, we describe the study methodology. In Section 3, we examine relevant literatures on product lifecycle management, decision theory, decision-making, and decision support systems, highlighting the limited research on decision-making in a PLM context. We derive a set of six principles for PLM group decision support from the literature. In Section 4, we describe a decision support structure that embodies each of the principles, which we use as a research instrument to undertake studies with organizations on PLM decision-making. In Section 5 we analyze three PLM decision problems with companies in different industries. In Section 6 we discuss the findings from the study and the potential in the future to exploit advanced information structures for decision-making in PLM. In Section 7, we discuss potential avenues for future work.

2. Methodology

We conduct the study in three stages. First, we use the literatures from PLM, from decision theory and decision-making, and from group decision support systems, to identify critical issues for PLM decision support within organizations. We highlight the absence of research that explicitly addresses decision-making in the PLM literature. Although classical decision theory is a mature discipline, the study of decision-making in real organizations identifies the limitations of the classical approach. It shows how decision-making in organizational contexts requires a broader set of contextual issues to be considered, including the need for problem exploration, often in a group context, before a clear understanding of the decision problem is gained. We also note that, although commercial PLM systems may provide powerful information systems and project management support, explicit support for PLM decision-making is limited or absent. From this basis we develop and discuss a set of six core principles to support group decision-making in product lifecycle management.

Second, we develop a research instrument to assist with investigating PLM decision support in organizations. The research instrument is a browser-based system built for PLM decision research purposes. The research instrument incorporates each of the six core principles identified in stage 1 and uses the concept of a decision as a core knowledge object that needs to be captured and stored in an organization's knowledge base. The six decision support principles enable an appropriate information flow to be specified around the knowledge object that captures a decision and its decision-making process. The structure supports the essential principle that a decision should be retrievable along with its relevant information for later audit or review, or for learning from or reuse of some aspects of the decision-making process. We stress that this system is a research instrument rather than commercial software for PLM.

The third stage of the methodology examines and validates the principles using PLM decision cases from contemporary practice through work with a group of industrial companies. We undertook a study with three diverse industrial organizations. Each of these organizations was interviewed using a semi-structured interview with a key contact with experience, involvement or oversight of decision-making in the context of PLM. One of the organizations was very large with significant information systems in place. The other two organizations were smaller SMEs involved in designing and manufacturing engineered products that varied in complexity. Neither of the smaller organizations had an existing PLM system. These three cases are used in this paper as exemplars of typical decisions that occur in these environments. We used the research instrument to carry out investigations on PLM decision-making with the partner organizations. We describe the cases and the approach to case study design and execution in more detail in Section 5.

3. Product lifecycle management and group decision support

PLM concepts have their origins in the Computer-Aided Design, Computer-Aided Manufacturing (CAD/CAM), and Computer-Integrated Manufacturing (CIM) systems developed since the mid-1980s. The challenges in capturing, storing and retrieving product and process related data, documents and information grew over the 1990s, resulting in the emergence of Product Data Management (PDM) systems (Gielingh 2008, Stark 2018) for use in all areas of product design and manufacture. As PDM systems developed, there was a growing realization of the opportunities for organizations to utilize and exploit the inherent value in product and process data generated over the whole product lifecycle (Saaksvuori and Immonen 2008). PLM systems began to emerge around 2001 (Stark 2015; Stark 2018) with the realization that aspects such as quality, cost, innovation and conformance to regulations needed to be managed throughout a product's lifecycle (Enríquez et al. 2018). Ameri and Dutta (2005) were some of the first authors to view PLM as providing not just technological solutions but as systems that could potentially provide sustainable competitive advantage to an organization that may be hard for competitors to replicate. PLM systems have proven particularly important for new product development with the continuing pressure on organizations to compress product development times and create new products and variants quickly (Stark 2018).

Corallo et al. (2013) review both academic and practitioner definitions of PLM to provide a contemporary view on what product lifecycle management encompasses:

"PLM - Product lifecycle management—is a strategic business approach that supports all the phases of product lifecycle, from concept to disposal, providing a unique and timed product data source. Integrating people, processes, and technologies and assuring information consistency, traceability, and long-term archiving, PLM enables organizations to collaborate within and across the extended enterprise." (Corallo et al. 2013)*.*

The product lifecycle can be viewed as consisting of phases such as Beginning of Life (BOL), Middle of Life (MOL), End of Life (EOL) (Papinniemi, Hannola and Maletz 2014). However, lifecycle phases can be labelled with different levels of granularity depending on the organizational and business context. For example, Saaksvuori and Immonen (2008), describe phases of definition, design, sales, manufacturing and service. Stark (2018) uses ideation, definition, realization, service/maintenance, and recycling/disposal. Others include product development, aftermarket, and end of product life (Schuh et al. 2008). A key concept in PLM is that knowledge and relevant data should be available from any lifecycle phase to use in any other (Hadaya and Marchildon 2012), enabling so-called closed-loop PLM (Kiritsis 2011). Such reuse of a shared body of knowledge should aid innovation (Ameri and Dutta 2005; Feng et al. 2017). However, complete coverage of the full product lifecycle is still rare in real implementations, with the earlier design and manufacture phases being more prominent in practice than later lifecycle phases such as the service phase (Kiritsis 2011).

Today's commercial PLM systems from major vendors such as PTC, Dassault Systèmes, Aras, Siemens, Oracle, SAP and Autodesk provide organizations with powerful IT support to facilitate the management of products as well as the management of information related to products and the processes used to produce them (Fleming et al. 2017; Stark 2018). Commonly provided support includes management of users and roles, and the provision of tools to support project management processes, stage-gate processes (David and Rowe 2016) and workflow management (Hayes 2017), although the sophistication of the project and workflow management tools varies. Tools to support user collaboration and communication exist in all systems although they differ in approach and integration with external communication technologies. Project management and engineering change management is typically supported (Wu, et al. 2014) but in different ways using different protocols for versioning, recording and managing change processes. As with all IT technologies in business and engineering, PLM systems continue to develop. Business Intelligence (BI) is a rapidly developing area and some of the major PLM systems have begun to provide BI support (Ogewell 2019, Zhang et al. 2017) but this tends to be focused on product design reuse. As PLM systems continue to develop they are becoming available on the cloud (Singh and Misra 2019).

The research literature highlights a number of challenges and opportunities for PLM systems, including the problems of data and information management (Brunner et al. 2007; Fasoli et al. 2011; Marra et al. 2018) and requirements management (Papinniemi, Hannola and Maletz 2014). The PLM definition presented by Corallo et al. (2013) encompasses well the managerial, informational, and collaborative

5

aspects inherent in managing products across their lifecycles. However, it is noticeable that neither decision-making nor support for decision-making in PLM are mentioned explicitly in the definition or in the literature. The implication is that information provision and information sharing alone will enable effective PLM processes both within an organization and with partners and stakeholders across the extended enterprise. In this study we focus specifically on decision-making and decision support in PLM. We first review key concepts in decision-making and then examine it in the context of PLM.

Classical decision theory considers a decision maker faced with clear discrete choices under various assumptions of risk and/or uncertainty (Beach and Lipshitz 2017). The challenge is to make a rational choice. Multi-Criteria Decision-Making (MCDM) methods add to classical decision models by seeking to satisfy more than one objective and/or by incorporating the decision maker(s) preferences in determining the best course of action. A wide variety of MCDM techniques have been developed (Velasquez and Hester 2013) including ELECTRE (Roy 1996), TOPSIS (Tzeng and Huang 2011) and AHP (Saaty 2008; Subramanian and Ramanathan 2012), as well as classical decision approaches such as Weighted Sum (Ishizaka and Nemry 2013) and Decision Trees (Hillier and Lieberman 2014). These techniques differ in the extent to which they impose formality on decision makers and the cognitive load and time burdens incurred in using them. MCDM tools are likely to be used for high impact decisions after significant problem exploration and information gathering.

Classical decision theory has been much criticized for not adequately capturing the nature of real-world decision-making and for being divorced from the 'messiness' of real decision-making in different organizational contexts (Simon 1977; Klein et al. 1993; Lipshitz et al. 2001; Beach and Lipshitz 2017). Simon (1977) developed the classical decision – making approach by highlighting the stages in a typical decision-making process – intelligence gathering, design (of the decision-making process), and finally making a choice. These decision-making phases can be further subdivided as shown by Turban, Liang, and Wu (2011). Zack (2007) argues that the characteristics of different decision-making contexts vary in terms of uncertainty (not having enough information), complexity (having more information than one can easily process), ambiguity (not having a conceptual framework for interpreting information), and equivocality (having several competing or contradictory conceptual frameworks). These require different types of decision support in organizations.

Naturalistic Decision-making (NDM) (Lipshitz et al. 2001) has sought to understand how decision-making is carried out in real-world settings, and how decision-making in such contexts can be supported. It acknowledges that decisions are often embedded in larger activity spaces and are made and contributed to by individuals and groups with different roles, different degrees of experience and expertise, and different levels of authority (Roy 1996). Decision-making in an organizational context is often intrinsically linked to exploration, understanding, interrogation, and problem solving. PLM decision-making, by definition, occurs in an organizational context and typically involves collaboration within a group. PLM decision-making contexts are often complex (Eigner et al. 2011), lack clarity at the outset and require a range of expertise and opinions to arrive at a decision solution, course of action, or outcome (Lentes and Zimmermann 2017).

The information systems support available for decision-making has developed very significantly over the last three decades. Sauter (2010) defines a Decision Support System (DSS) as a "*computer-based system that supports choice by assisting the decision-maker in the organization of information and the modeling of outcomes*." Historically, decision support systems tried to support a single decision maker in making one-off decisions (Hosack et al. 2012). As computers became networked and gained the ability to facilitate communication, the concept of Group Decision Support Systems (GDSS) began to emerge. In one of the seminal papers in the field, DeSanctis and Gallupe (1987) defined a GDSS as a system that aims to: "*improve the process of group decision-making by removing common communication barriers, providing techniques for structuring decision analysis, and systematically directing the pattern, timing or content of discussion*". GDSS tend to allow planning and structuring of the decision-making process as well as brainstorming to generate new ideas. DeSanctis and Gallupe (1987) noted that a GDSS could "*alter the communication process within groups*". In later work they note that GDSS should accommodate a wide range of decision-making processes and provide tools to support social needs as well as task-related ones (DeSanctis et al. 2008). The advent of the web has accelerated and broadened such system-enabled communication to become not just technically easier, but ubiquitous (Vinge 2006; Stei, Sprenger and Rossmann 2016).

Roy (1996) highlighted that a range of actors may contribute to a decision-making process in different roles. Participants in decision-making processes in organizations may vary in the intensity of their involvement, their contributions and in their impact on decisions (Edmondson and Nembhard 2009). This idea of multiple participants with different roles is a defining characteristic of PLM decision-making. In many organizational contexts, defined processes or protocols must be followed for PLM decisions and may need to be supported in group decision-making (MacCormack and Verganti 2003; Saaksvuori and Immonen 2008). However, flexibility in decision processes is also important for many engineering decisions (Eigner et al. 2011). Iterative processes are important to allow new information to be integrated and the best solutions to be developed (MacCormack and Verganti 2003). Ideally new projects learn from previous ones to reduce the likelihood of repeated mistakes or to avoid the reinvention of solutions already developed by an organization. Each of these issues is relevant to decision-making in a PLM context where creative elements (e.g. in new product development) may need to be balanced with the control needed to manage an organization successfully.

PLM systems contain and/or support the use of specialist software tools that are crucial to decision-making (Messaadia et al. 2016). For example, CAD modelling tools are central to PLM (Enríquez et al. 2018). Kärkkäinen, Pels and Silventoinen (2012) view the support for, and integration of ICT tools as central to the question of PLM maturity, with even the lowest level of PLM maturity assuming the use of ICT tools in an organization. GDSS now tend to include collaborative tools which can be used for virtual decision-making (Turban, Liang and Wu 2011). Tools are available that can structure and store decision components such as mind maps, voting, and MCDM (Roy 1996; Tzeng and Huang 2011; Subramanian and Ramanathan 2012; Velasquez and Hester 2013). In the case of PLM this also includes tools for engineering specific decision-making.

The decision-making literature in general and the PLM literature in particular are limited in discussing how decisions and decision processes should be recorded in organizational knowledge bases. However, a decision is an important element of organizational knowledge and how it is represented and captured is critical in PLM contexts. Hamzah and Sobey (2012) argue that business metadata needs to be integrated into the decision-making process, including information appropriate to a manager's role. A schema called the '*Common Decision Exchange Protocol (CDEP)*' has been proposed for storage, reuse and sharing of decisions (Blomqvist et al. 2010; Waters et al. 2010). This is designed to structure decisions for storage and exchange. CDEP defines a minimum level of structure and attributes, but also shows how other aspects such as states of a decision, the participant decision makers, and supporting information can be stored within the decision. Attributes may need to be stored about a decision such as: "*who*, *what*, *where*, *when*, *how* and *why*", options, decision criteria, confidence, sub-decisions, notes, references, and the states or stages a decision may pass through. MacCarthy and Pasley (2016) argued that the recording of such contextual information about the reasoning around a decision is very relevant in PLM as it moves beyond merely recording information to recording the process of decision-making and the results or outcomes of a decision process. Feng et al. (2017) designed a schema for smart manufacturing, which contains an entity to store decisions, but storing decisions for reuse is not the main focus of their work.

How information is structured in a PLM system is important. Gruber (1995) describes an ontology as '*an explicit specification of a conceptualization*', which can be used to capture domain knowledge in terms of entities and their inter-relationships. El Kadiri and Kirirtis (2015) reviewed ontology research in the context of PLM and identified seven key roles that information ontologies may fulfill in future PLM. They conclude that ontologies are central to solving data integration problems, with initiatives such as OntoSTEP being developed. Currently such efforts are focused on product data interoperability rather than activity-based interoperability (Lentes and Zimmermann 2017). However, there is little or no explicit discussion of the need to, or the processes by which decisions and their related information should be captured and recorded in PLM systems. We argue that PLM systems can benefit from such thinking.

3.1 Research Gap - Principles to support PLM decision making

It is clear from the literature review that PLM decision-making processes have not been examined explicitly in research studies. Given the importance of decision-making in the effective management of products and related processes over their lifecycle, this is a significant research gap, which we address in this study. The decision-making literature and the group decision support literature provide insights on effective decision-making that can be adapted for a PLM context. In Table 1 we summarize their relevance and importance for decision support in PLM. We then develop a set of principles to support PLM decision-making which we discuss below.

Table 1: Decision Support Issues

Issue	Relevant literature	How to address to support PLM decision-making
PLM decisions manifest themselves in many different forms, which require different decision-making structures and approaches.	Zack (2007); Ullman (2012); Simon (1977); Roy (1996); Klein et al. (1993); Lipshitz et al. (2001)	Acknowledge that different contexts may require very different decision structures, stages, and approaches. Allow for the dynamic planning of the decision-making process to suit the context and to conform to pre-defined PLM processes. See **Principle 1** below.
Multiple participants may contribute to PLM decisions - relevant groups, departments, and other stakeholders within different organizational structures and hierarchies.	Marra et al. (2018); Roy (1996); Zack (2007); Turban, Liang and Wu (2011); Eigner et al. (2011); MacCormack and Verganti (2003)	Within the stages of a decision-making process, associate relevant participants with these stages and give each participant a specific role. Assign one participant as a Principal Decision Maker (this term is explained in the discussion below). See **Principle 2** below.
PLM decisions may require the use of a diverse set of relevant tools, which may be used at any stage of a decision problem.	DeSanctis and Gallupe (1987); Messaadia et al. (2016); Enríquez et al. (2018); Kärkkäinen, Pels and Silventoinen (2012)	Within the stages of the decision-making process, associate the tools used with each stage. Capture the content of the outputs of these tools where possible. See **Principle 3** below.
Contemporary PLM systems must enable collaboration, mandatory consultations, and record inputs, contributions and changes made in all system interactions.	Stei, Sprenger and Rossmann (2016); Ullman (2012); Cardon and Marshall (2015); Turban, Liang and Wu (2011); Vinge (2006)	As far as possible, relevant communication should be captured in an appropriate level of detail; it can be used to allow better retrieval of knowledge. Collaboration 2.0 concepts can provide context for the reuse of knowledge throughout the product lifecycle. See **Principle 4** below.
Previous PLM decisions and decision processes should be traceable and retrievable for review, audit and reuse across product ranges.	Hamzah and Sobey (2012); Blomqvist (2014); Blomqvist et al. (2010); Waters et al. (2010); El Kadiri and Kiritsis (2015); Lentes and Zimmermann (2017)	Using the context provided by a formal decision-making approach with stages, participants/roles, and their communication, previous decisions must be capable of being recalled specifically in order to be reviewed or audited. An information retrieval system should have the potential for reuse for similar decisions or to inform future decisions. See **Principle 5** below.
PLM decision problems manifest themselves in many different forms.	Eigner et al. (2011); Kärkkäinen, Pels and Silventoinen (2012); El Kadiri and Kiritsis (2015); Messaadia et al. (2016); (Lentes and Zimmermann	Flexibility should be balanced with formality in capturing PLM decisions. **See Principle 6** below.

	2017); Enríquez et al. (2018); Marra et al. (2018)	

Principle 1 (P1): *Effective group decision support for PLM should facilitate and enable the planning of any decision through a desired number of decision-making stages, identifying what should occur in each stage and the collaboration that should take place.*

PLM decision problems may manifest themselves in many different forms (Zack 2007; Ullman 2012), from the highly structured, where the organization is well versed in the process needed to identify the most appropriate course of action to those decisions that require greater levels of exploration and framing before an appropriate decision can be made. The stages that are needed in a decision-making process should, therefore, be customizable to be appropriate for the decision type and context. The stages defined by Simon (1977) or Roy (1996) may suit some decisions. However, many PLM decisions will require more, fewer, or different stages for different decision types. This may depend on the organizational structure (see P2) and may need to conform to pre-existing processes where a PLM system is in use. These stages might change dynamically during the decision-making process based on the results of exploration. The stages in a decision process may include or require collaboration between different functions or groups within an organization or between organizations.

Principle 2 (P2): *Effective group decision support for PLM should facilitate and enable group collaboration on a decision problem but within a decision-making hierarchy, which must include a Principal Decision Maker.*

PLM decisions require inputs from different participants, groups, departments, and other stakeholders (Roy 1996; Marra et al. 2018), some of whom may be outside the organization (e.g. a material or machine supplier or a consultancy organization). The nature of individual or group inputs can vary, as well as the roles that individuals or groups play in any decision-making process. Companies of different sizes typically engage with decision support in different ways (Zack 2007). Many companies take decisions in a predominantly top-down way (Roy 1996), whereas some organizations today encourage a more bottom-up approach to collaboration (Turban, Liang and Wu 2011). Group decision support for PLM should be able to reflect an organization's needs and current PLM processes. It should not force an inappropriate organizational structure onto decision makers.

Many people, groups or functions may be involved in the complex technical decisions that are characteristic in PLM. We use more specific role titles than the broader term 'stakeholder' favored by Roy (1996). However, although multiple collaborators may contribute to, comment on, or provide critique on a decision problem, in a PLM context an individual, a group of individuals, or a specific department or function will ultimately be responsible for agreeing or ratifying a course of action. This will often reflect the hierarchy within the organization. Roy (1996) notes that this stakeholder "*plays a critical role in the evolution of the process*". We term this responsible entity (individual, group,

10

function or organization), the Principal Decision Maker. The Principal Decision Maker will typically plan the decision process by defining the stages of the decision, the activities that should occur within each decision stage, and who is involved, in accordance with Principle 1 above. Ultimately, the authority to make the decision and the responsibility for the decision in a PLM context will rest with the Principal Decision Maker. For instance, a new design to address a known quality problem may involve a decision on material selection made by a specific group within a company, the specification of a control system by another group or function, and the completion of viability tests performed and signed off by another group. However, before the design solution is implemented, the Quality Assurance Director (the Principal Decision Maker) needs to approve the final proposed solution. Functionality for the definition of users and roles within existing PLM systems may assist in the application of P2.

Principle 3 (P3): *Effective group decision support for PLM should facilitate and enable the use of relevant decision-making approaches and tools at any stage of a decision problem.*

Some PLM decisions may require a high level of formality and need to be supported using specific decision tools at particular stages of a decision process. Tools such as CAD/CAM and document management are embedded in most PLM/PDM systems (Messaadia et al. 2016). Examples of MCDM approaches such as AHP were given in the literature review (Roy 1996; Tzeng and Huang 2011; Subramanian and Ramanathan 2012; Velasquez and Hester 2013). PLM decision support should enable the use of relevant tools at any stage of a decision problem within the context of existing organizational processes (see Principle 1). The tools used at any stage of decision-making process should be recorded and traceable to understand how a decision was arrived at or the basis on which it was made (see Principles 5 and 6).

Principle 4 (P4): *Effective group decision support for PLM should facilitate and enable engagement, commenting, and conversation by the participants in a decision process*.

PLM decision-making should encourage and foster collaboration in the decision process by supporting communication between participants, when this is appropriate, and/or when it is mandated in organizations. Effective PLM group decision support should be capable of facilitating and gathering rich communication and interaction dialogues. This can be stored with decisions, as well as logs of inputs and changes made in all system interactions, to allow for traceability of the process by which a decision outcome was arrived (see Principle 5).

Principle 5 (P5): *Effective group decision support for PLM should facilitate and enable retrieval, review, and reuse of previous decisions, decision processes, and all their supporting information.*

A central aim of PLM is to allow information gathered from any phase of the product lifecycle to be used in any other (Hadaya and Marchildon 2012; David and Rowe 2016). Reuse of decision information and decision processes is a necessary and valuable part of effective support (Antunes, Freire and Costa 2016). Thus, every decision and its decision process should be traceable and retrievable in PLM. This should be possible across product ranges for effective PLM decision-making to

allow a previous decision and its associated decision process and information to be retrieved for use in later similar decisions with a different product or process. Retrieval should allow all stages of a decision process and all content to be searched, reviewed, and audited without extensive use of generic communication media such as email. Storing and retrieval of decisions and related decision processes can assist in addressing current decision problems. Functionality for information retrieval within some existing PLM systems may assist in the application of P5 and may be enhanced if decisions are recorded as distinct units of knowledge (see section 4).

Principle 6 (P6): *Effective group decision support for PLM should facilitate and enable a wide range of decision types and decision contexts that arise in organizations, from the simplest to the most complex, at any stage of the product lifecycle.*

PLM decision support needs vary widely across organizations and decision types. PLM decisions vary in complexity from clear and direct decisions to much more complex decision scenarios. The PLM literature describes different granularities of PLM phases (Saaksvuori and Immonen 2008; Schuh et al. 2008; Papinniemi, Hannola and Maletz 2014). Many schemes focus on directing useful information from later phases to the design processes. For others, the key aspect is recording early decisions and following them through to product use. For some organizations, PLM concepts are important across the entire product lifecycle (Stark 2018). Management style and stakeholder involvement vary across organizations. Thus, there is great diversity in the potential range of PLM decisions, when they may occur in the product lifecycle, and the support that may be needed.
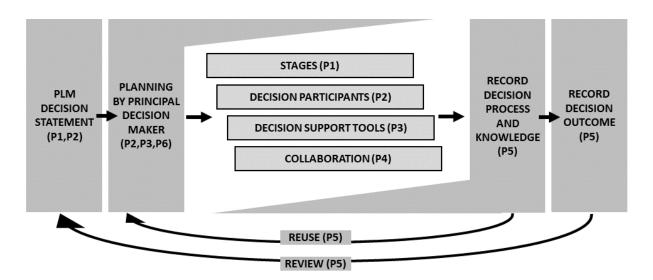
4. Developing a Research Instrument

In order to capture a decision as a distinct unit of PLM organizational knowledge embodying the six principles above, it should have the following components:

1. **Decision stages**. A PLM decision proceeds through a set of stages, which must be defined. Typically, the stages in a decision process allow the participants to become more informed about the decision context and to reduce the uncertainty to a point where a choice can be made between different or competing options or courses of action.
2. **Decision makers**. Some PLM decisions may be made by a single decision maker while others will involve multiple participants, each of whom may differ in the role they play in the decision process. A PLM decision will always require a **Principal Decision Maker** with the authority and/or responsibility to make key decisions or adjudicate on key parts of a decision. The Principal Decision Maker could be an individual, a group, a department, or a function within an organization. Other participants in a PLM decision process may be involved to provide or to gather relevant information or provide inputs or comments that shape the decision and/or the decision-making process.
3. **Decision-making approaches and tools**. A wide range of tools, methods, models and techniques may be used in PLM decision-making. These vary from approaches such as models used to enact a business process through to tools for structuring decision information, and tools to undertake

technical analysis and make technically led decisions. These may already be available and in use in an organization and may be integrated into support structures for PLM decision-making. The tools that have been used in a decision-making process, how, when, by whom, and at which stage, should be recorded.

A generic information flow capturing a decision as a unit of PLM knowledge and embodying each of the six principles is shown in Figure 1. Knowledge objects (Clermont and Kamsu-Foguem 2018) link relevant information together. In this case, the decision stores or references different types of content, collecting them together in one unit. The left-hand side shows that the decision problem needs to be first articulated and then the decision process must be planned. These activities will be driven by the Principal Decision Maker in a PLM context. Planning may continue dynamically as the decision is explored and further information comes to light, as shown by the taper in Figure 1.

Figure 1: Information flow for a generic PLM group decision support structure

Four essential aspects of a decision support structure are identified in the center – user-defined decision stages, user-defined decision participants, user-defined decision-making support approaches and tools, and collaboration. The flow must support a flexible number of participants in a decision and, critically in a PLM context, must also support existing organizational structures and hierarchies, which can allow the assignment of specific decision participants to specific decision stages. Different decision support approaches can be associated with each stage. Collaboration is facilitated within a decision support structure by the mechanisms provided for communication, interaction, and commenting. The right-hand side panels in Figure 1 show that these components are recorded as the decision-making process proceeds, ultimately facilitating the transition from the decision statement to the decision outcome.

The metadata associated with the decision object facilitates the storage and subsequent reuse of decision information in PLM within and between phases of the product lifecycle. Defining a decision as an information object in this way allows the decision outcome to be recorded, reviewed when

necessary, and reused for similar related decisions in the future. The recorded decision process might also be used by the planning stage in later decisions and the recorded decision outcome might be used in the definition stage of later decisions.

We have embedded the PLM decision support principles, the information flow in Figure 1 and the decision metadata that can be derived from it, in a PLM decision support structure, which we use for research purposes on PLM decision-making. The decision metadata relate directly to the principles, including stages (P1), roles and hierarchy (P2), decision support tools data (P3), relevant comments and discussion (P4), and the overall context for the decision (P6). The metadata supports decision retrieval and reuse where appropriate (P5). The research instrument was created using the LAMP paradigm (Nixon 2014). It is browser based to make it easier to demonstrate the principles to partners in the project. It is one possible implementation of the principles. It is sufficiently flexible to be applicable to different decision-making contexts, allowing flexibility for different types of decision processes and pre-existing organizational protocols, processes, and workflows. The research instrument allows the PLM decision to be worked through with an organization in an interactive manner, assisted by a researcher, to capture each element of a PLM decision and the decision-making process used to address it. It was not our intention to develop commercial decision support software, but to develop a research tool to investigate, validate and demonstrate decision support principles.

Four iterations of development of the research instrument were implemented to use with our partner companies. Between iterations we took a step back to evaluate the research instrument to ensure it embodied the principles previously outlined and facilitated and enabled the capturing of PLM decisions across a wide range of contexts. We briefly describe how the research instrument embodies the principles below. A sample screen from the final version of the research instrument is shown for illustrative purposes in Figure 2 below.
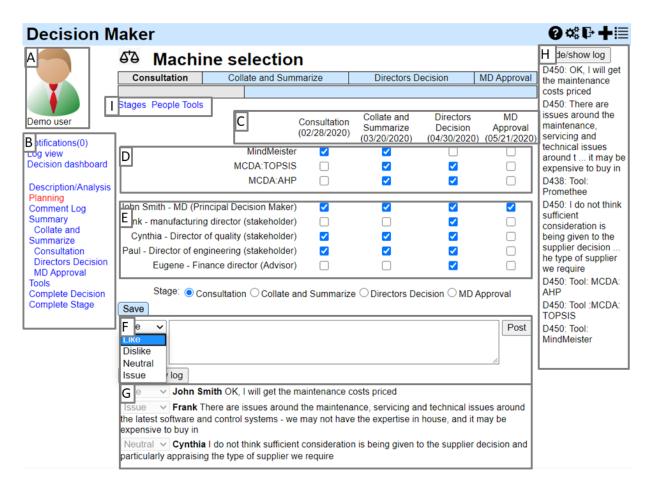
Figure 2: Sample screen from the research instrument

Figure 2 shows the decision planning screen from the research instrument, populated with illustrative generic content. Its components are enclosed in grey rectangles and labelled by letters: **A:** picture and name of the currently logged in user. **B:** the main navigation menu, which adapts as decision stages and associated tools are added. **C:** the stages of the decision, which can be edited. A matrix associates stages to participants **E:** and tools **D**. **F:** the multi-value "like" button and comment entry box. **G:** previous comments displayed chronologically. **H:** a timeline of comments and logged events. **I:** menu items allowing editing of stages, participants and tools linked to this decision. During the decision-making process, any aspect can be changed by the Principal Decision Maker - the participants, the stages, the decision support approaches, the tools used, or the number of iterations needed for a decision outcome. We highlight below how each of the principles is satisfied by this generic structure.

P1: The structure allows the stages in a decision-making process to be defined, which generates a decision-making workflow [C]. Both the group structure and the nature of collaboration can be controlled [D, E]. Participants may vary in the intensity of their involvement and contributions in each decision stage. Tools and participants can then be linked to these stages [D, E, I]. The level of decision planning appropriate for each decision context can be varied. Our cases suggest that decisions such as production issues for simple products can often be more formulaic and specialized, whilst other decisions may involve multiple stages of engagement and consultation. Stages are associated with end dates that act as a workflow for the decision. Participants can be selected for each stage from the

users currently registered in the system. This allows parsimony in communication to limit the number of decision support options needed for each stage.

P2: We assume the existence of a Principal Decision Maker with the authority to lead a group in a decision-making context. The Principal Decision Maker may be supported by co-decision makers in an environment where other potential participants and/or stakeholders can be invited to contribute or be consulted on some aspects of a decision. It is possible to define participants, either all involved in the same stage or stages, or passing control across several stages. Each participant has a decision specific role, e.g. Co-Decision Maker or Consultant. These can be assigned to participants via a planning screen [I]. Role titles can be customized. An organization's pre-existing management structures, functions and hierarchies can be defined within this structure. Decision participants can be involved only where needed [E]. Any participant assigned to a stage has access to information about that stage only.

P3: The structure supports the integration of any relevant decision approach tools [D] at any stage. Since an organization may already have preferred tools, the structure facilitates their integration in a flexible way. In the research instrument, the tool set comprises MCDM approaches, and visualization tools. Visualization tools such as mind mapping software (Buzan 2006) allow graphical information structuring and are likely to be used in exploratory and problem understanding stages. More formalized MCDM approaches may be useful once the choices and important criteria of a decision have been defined. Once a tool is deployed in a decision and is populated with relevant information, this information is linked with the decision stage in which it is used.

P4: Group decision-making necessarily involves human communication. Commenting is allowed at any stage of a decision problem for participants assigned to the stage [F]. The research instrument incorporates functionality such as threaded commenting [G], a 'like' button [F], notifications, and status screens [H]. Logs of comments and stages are stored for ongoing decision problems [G, H]. Comments are attached to decision entities such as stages and tool contents, reducing information overload that may result from a more general commenting approach. The comments in [G] are displayed for the current decision. Any action taken such as adding data, changing field values, attaching tools or completing a stage is logged. A summary log is available to a user [H], allowing quick access to active decisions and awareness of changes in their current workload. Participants are kept engaged in the decision-making process across several decisions by a notification stream [H], showing an overview of decisions they are involved with. The most relevant activity in the most important decision activity is shown first [H].

P5: The reuse of information such as the decision-making structure, stages, approaches and tools used, participants and their various inputs and comments, is central to PLM. The decision metadata stored by the research instrument is derived from the principles and information flow described above. Whilst a decision is live, information is stored to allow search and reuse of decisions. When a decision is completed, information about that decision is stored to add to the decision-making experience in the organization. Snapshots of the content of the decision support tools are recorded

when a stage is completed and can be viewed in stage summary screens. Comments and logs in the system are recorded as a detailed record of the decision-making process. Retrieval also supports decision auditing and the recording of commitments to actions.

P6: The research instrument allows a very flexible approach to decision-making. Tools, stages and roles can be used to the degree considered necessary (or not at all) for the current decision problem. A basic decision may be simply recorded but the functionality can be used to support all aspects of a multi-stage decision-making process for a more complex decision problem.

5. Case Study Analysis Using PLM Decision Support Principles

We undertook case studies with three industrial organizations to investigate and validate the relevance of the decision support principles in supporting PLM decision problems arising in contemporary practice. We visited each organization to establish a working relationship and to understand their PLM decision context. Below we summarize each of the cases and their contexts. In the analysis we examine and illustrate the relevance and use of the six principles embodied in the generic prototype structure and show how the principles in combination provide support for effective decision-making processes.

We selected one decision given to us by each organization. In each case we sought the agreement of the organization that it was a recent typical decision and had implications with respect to their product lifecycle management. Each case ultimately requires choosing between several options but only after significant preparatory work. The options are refined, and the criteria on which the selection is made are explored. The differences between the cases are in the industrial and organizational contexts, and in the scale and complexity of the decision problem. We worked with the organizations to consider the approach and by analysis showed how the principles assist in the cases. We analyze each case with respect to each principle, highlighting how the decision-making process can be managed and supported.

In each organization we carried out a semi-structured interview with a key contact with experience, involvement or oversight of decision-making in the context of PLM. We had familiarized ourselves with the decision, its context and how it was typically made, who was involved and the issues that typically arise. We used the research instrument to focus the interviews on the decision and its context in order to assist in the feedback process. We had previously populated the research instrument with data derived from our study of the relevant case decision provided by the case company. We collected further data about each of these exemplar decisions remotely using internet telephony with screen sharing. The contact in each organization was given access to the research instrument before the video call and had access to it and our screen content throughout the call. We first introduced the research instrument and outlined the functionality and principles. We showed how it could be addressed in a more formal manner with the research instrument that incorporates the principles. We discussed the decision with each respondent, at the same time taking note of comments, issues and views. We used the research instrument to discuss the decision-making process that the organization

would follow. We used this to examine whether the six principles would bring benefits. As will be seen, the decision as laid out here addresses each organization's issues and brings additional benefits of a formalized, retrievable and auditable PLM decision process.

5.1 Company A (New Spring Making Machine)

The case selected for Company A occurs within an SME company with fewer than 100 employees that manufactures very small precision springs and develops novel engineering solutions for its customers. The company has a requirement, which has emerged over a period of 4 months, for a new spring making machine to respond to a customer requirement to manufacture springs for a specific market. The decision problem centers on which machine to choose from which supplier for the new range of springs. The decision will affect many aspects of product development and product lifecycle for springs in this market. Although not a complex decision environment, the value in recording the decision process and the decision outcome is high. This is an environment where technical skills, knowledge, and expertise were at a premium and at the time of the study there was significant turnover of skilled engineering staff. Recording and retrieval of such decisions would allow a newly recruited Chief Engineer to gain knowledge rapidly and to be able to use or enhance the decision process for future decisions of this type. We analyze the case with respect to the principles in Table 2.

Table 2: Company A (New Spring Making Machine)

P1	- The decision involves three people. This context is relatively stable and would apply in further similar decisions. - In the prototype the decision is recorded in a single stage without the use of further tools. - Necessary information is gathered when needed, rather than as a separate stage since the same people are involved in information gathering and the decision-making process.
P2	- The decision makers are in daily contact, there is no need for extensive communication to be facilitated. However, it is important that all key points affecting choices are formally recorded. - In a small company, such decisions must ultimately be approved by the Managing Director, thus they are the Principal Decision Maker. Other stakeholders are the Chief Engineer and the Finance Director.
P3	- Additional tools to support the decision-making process are not needed. - Much of the information gathering during decision-making is done manually, following a familiar knowledge gathering process.
P4	- Since most of the communication is done informally, the requirements for communication and commenting are straightforward.

P5	- This company produces miniature sized engineered products, which may require novel engineering solutions and the acquisition of new machinery. Reusing decisions about early versions of these products can potentially save a lot of work rediscovering forgotten techniques, particularly in the context of staff turnover in the technical workforce. - Although it is a straightforward choice, this decision, along with other recorded decisions and supporting information, could help a newly recruited Chief Engineer understand specialized technical aspects of the products and how they are made, something the firm had struggled with previously.
P6	- Some constraints already exist within the decision context because of knowledge of the organization with the capabilities of a small set of machines made by three machine manufacturers. - Within these three machine suppliers, various criteria may affect the procurement decision, some of which are only indirectly related to the machine itself, for example the skills required in programming the machine and the availability of those skills.

This decision is one taken by a small number of people. It is not very complex and requires no additional decision-making tools. However, it is important for this SME to make an informed decision as it will affect its manufacturing capability in the future. Hence, recording the decision process, key communications and criteria could prove very useful in helping a new Chief Engineer understand the common requirements needed to evaluate and choose suitable spring making machines for this organisation.

5.2 Company B (Autobagger for Existing Product)

The second case (Company B) is more complex. It also occurs within an SME employing just over 100 people making precision medical equipment. For greater control of product quality, a need was identified for an auto-bagging machine to be chosen from a range of machines sold by one machine manufacturer, the market leader in the field. This was the first use of such a machine in this company that operates in a highly regulated market. The decision therefore needs to be recorded as a process change in the product lifecycle. The decision requires considerable intelligence gathering both within the organization and with the supplier on the capabilities of different machine options and customizable machine add-ons. Retrieval and reconsideration of all aspects of the decision process could be necessary if the technical solution chosen resulted in either quality failures or subsequent productivity and throughput issues in production. We analyze the case with respect to the principles in Table 3.

Table 3: Company B (Autobagger for Existing Product)

P1	- Up to 5 people and 3 stages are identified, tools are used for information exchange and representation, but not for analysis. A workflow of three stages is set up. Each can be described at an overview level, providing milestones as the decision proceeds. Key discussions are recorded against the appropriate stage. Specific tools are restricted to the relevant stage; and similarly for communication such as commenting.

	- The information needed for the decision cannot be gathered at the start, as it will emerge from experiments conducted with the various add-ons to the auto bagger, thus in this case the stages control the evolution of the decision problem. - The default stages – intelligence gathering, design (of the decision) and choice - were appropriate and valuable for this case. The experimentation was carried out in the intelligence gathering stage with multi-disciplinary input. This resulted in enough information about the decision to allow it to be designed as a set of choices. The final stage selected one of those choices based on the input of the Principal Decision Maker.
P2	- Different people are involved in the information gathering phases and the decision-making phases. Assigning appropriate people to stages reduces unnecessary cross talk between groups that do not need to be involved. Key findings can be communicated using the stage summary screens as the decision moves forward towards the final stage. - This company is small enough that the core management team are involved in the sign off of this purchase decision rather than delegating that responsibility. It is likely to be an item noted and signed off in a board meeting, the company board is the Principal Decision Maker.
P3	- Some use of tools allows for the options to be managed as the decision moves towards clarity. For example, the machine options are organized using a mind map, which allows simple structuring of criteria.
P4	- Engagement is fostered between the company and its potential supplier by capturing the communication between the two. Internal communication is limited since all participants are in regular contact. However, recording of key communication is valuable, including with suppliers.
P5	- The decision is specific in nature. It will be valuable to understand how it was dealt with after the decision is implemented should problems arise with the auto-bagger or with regulatory authorities. - The likelihood of another decision with precisely the same parameters being taken in the future (e.g. choice of an autobagger) is low. However, this pattern of decision-making is very likely to reoccur in this medical equipment manufacturer. Thus, the decision process may well be reused. - The decision is stored for review in case of a product or process related issue such as a recall.
P6	- The product that required bagging affects the machine accessories purchased and how the machine was set up, as well as how it was integrated into the existing manufacturing processes. This required consultation with the supplier who test bagged samples of products in order to understand the potential throughput rates. A cost benefit analysis was also performed and had to be signed off, requiring flexibility in decision-making structure.

This more complex decision has been structured in line with the principles. This allows participants to understand which stage the decision is at, and to be involved only when they need to be. The research instrument has been used to record the discussion about the setup of the autobagger made in collaboration with the supplier. As well as this, and in common with the first case, the criteria for selection have been recorded. The decision process used may well be reused for a product or process related issue arising again in this medical equipment manufacturing context.

5.3 Company C (Consultation on New Manufacturing Facility)

The most complex case concerns a project in a large company with over 1000 employees. This organization has a desire to instill more formality in PLM decision-making and enable more decisions to be revisited, reviewed, and audited. The case consisted of a consultation process with another large company in order to select a best concept for a new manufacturing facility for the assembly of large engines. The set up was novel, using one production line to produce 3 different products. As well as solving technical issues relating to this, design of the plant would have the typical concerns for supply chain, storage, geography, and constraints on layout such as building height. Further restrictions and requirements were based on the philosophy the consultancy used including adopting both lean and green manufacturing solutions.

Despite there being nine participants in the decision process, there were only three people who could substantially influence the outcome - the consultancy representative, the manager of the proposed plant (the Technical Director) and the Director of Operations of the proposed plant. The others were workers council and safety representatives, internal operations, head of product design, construction and building, Director of a downstream facility, and the Head of Logistics. The vision was to develop a more streamlined PLM decision-making process that would require fewer participants, reduce the number of unresolved issues and that would, ultimately, reduce the complexity of the final meeting that agreed plant design.

The original workflow for this decision had culminated in a very long meeting where a choice was made between seven layouts, each of which was the result of considerable work. This meeting revealed that the workflow had resulted in errors and missteps. Some of these were glaring errors when seen in the light of the meeting, for example two of the layouts contained fundamental assumptions about the size of the factory floor which did not fit the actual constraints, and two others did not use Lean principles, a fundamental tenet of the consultancy's design approach. These four were rejected almost immediately but had represented a considerable amount of work. Using this case as a basis, a better decision workflow could be designed within the organization. We analyze the case using a more formalized approach with respect to the principles as described in Table 4.

Table 4: Company C (Consultation on New Manufacturing Facility)

P1	- Customized decision-making stages are needed to focus communication, to allow management of the decision-making process and to focus the use of tools. The first stage is purely for the planning of this complex decision-making process, and the others follow an information structuring pattern. The stages were dynamic and evolved during the decision. - The organization needed to first to create layout options through the consultation process before a 'best choice' could be determined. With a more structured information gathering and recording process, errors can be reduced. For example, the constraint on the factory floor size becomes common knowledge early on and not in the final meeting, and the two layouts breaking the constraint are, therefore, eliminated and not developed in detail.

P2	- The approach needed to cope with a multi-stage dynamic process that evolved in the course of the decision and that could involve high levels of commenting to allow different points of view to be captured at each stage. - The company stated that these types of decision typically involve many people. In the case there are 9 participants. Given the number of people involved, communication is complex, with the commenting system being used to allow different points of view to be aired and to keep participants up to date with developments, e.g., when the constraints are entered on the system all users can see them and respond. Although this may lead to a lot of communication between people who are not usually involved in these decisions, this can lead to participants contributing in a way that is less risky for them than in open meetings. The ability to associate people to stages can reduce the level of irrelevant communication. There will still be a final meeting, but fewer issues will remain unresolved at the final stage. - In parallel the consultancy representative and the higher management of the new plant have been communicating their issues via email. The results of these private discussions could be recorded in the research instrument. Although this still results in 'siloed thinking', it is less so than before and consensus can be partly reached without it becoming a conflict in the final meeting. - In the new workflow the final decision could be delayed until the meeting with fewer people who could disrupt the selection of the overall best concept. - Although the meeting must take place to gather all final opinions, the ultimate Principal Decision Maker is the future manager of the plant.
P3	- This case uses decision support tools more heavily, a mind mapping tool within the system is used to map the decision options and criteria early in the process and allow the participants to have a structured record of key issues. This information is stored against the early stages of the decision. The use of tools evolves as more is learned about the decision context. Later, a more complex mind map is created leading to the use of an MCDM technique. The results of the MCDM analysis is stored and used to inform the final board meeting and for later retrieval. The organization uses many standardized lists and matrices to check that conditions are right. - The structure is flexible enough to incorporate a range of tools used in the process and summarize their outcomes, e.g., storing an exploratory mind map developed at an early stage. - The organization uses simulation to decide between production floor layouts. The research instrument can store the output of these simulations.
P4	- There is complex communication at several levels and amongst several people. Using the stages and the planning screen, communication in the early stages concerning technical detail is kept to those best able to manage it. - As the decision process progresses, notifications keep people up to date with comments and changes to the decision status. - The final decision needs to be made in a face to face meeting. The research instrument becomes a recording device for the decision made final meeting, rather than being used to manage the negotiations.
P5	- It was acknowledged that the cycle of decision reuse could become a key business advantage to this company, which has a consultancy role within a large company. Whilst the projects undertaken differ in detail, they are all manufacturing design projects. Similar decisions are made in these projects by people in similar roles. - The stages of a decision define a workflow for a decision.

	- Email trails were found not to be sufficiently structured to recreate decision outcomes or their context. A stated requirement by this case partner is for decisions to be recorded in detail so that those involved can revisit the rationale and avoid renegotiations. - A stated aim was to incorporate decisions as branch points within a broader PLM workflow. Thus, decisions could be recalled when they are at the same or have similar decision points to provide information and decision-making structure. This could lead to changes in processes and protocols of the organization.
P6	- The current process used by the company for facility design is cumbersome and can be refined by using the prototype decision structure, and decision processes can be further customized for specific facility design projects. - This is a very complex example, currently involves 9 people in 2 organizations, involving many departments of the client company. There are several undefined stages. The decision requires informal and formal use of tools for exploration, knowledge gathering and support. - The client context for a future project could differ extensively for each facility design project, but many elements of the decision problem maybe similar.

This very complex decision has been structured in line with the principles. This allows participants to understand which stage the decision is at, and to be involved only when they need to be. The research instrument has been used to record the discussion about a variety of issues over a number of potential solution layouts. This has been carried out across multiple functions in the organization, and with the consultant organization (our case company). As well as this, and in common with the first two cases, the criteria for selection have been recorded in detail, as well as multiple supporting analyses. This complex decision has been streamlined by adherence to the PLM decision support principles.

6. Discussion

The literature review shows that PLM research is weak in acknowledging the central role of decision-making. However, the need to record, retrieve, and re-use decisions made across the product lifecycle is noted and hence the need for effective facilitation of PLM decision-making is evident. The aim of this work was to establish principles that can support PLM decision-making, which PLM systems should facilitate. We argue that PLM decisions are critical and distinct units of organizational knowledge that need to be captured explicitly in PLM processes and recorded in PLM information systems.

We have identified six principles to support effective PLM decision-making, which we use to determine the metadata needed to specify, capture, and record a decision process and its outcome(s) as a critical and distinct unit of PLM knowledge. From the principles, we derive an information flow and a decision support structure to provide effective PLM decision support. PLM decision-making typically needs to be carried out within an existing organizational hierarchy and potentially within existing PLM processes and protocols. However, it also needs to allow flexibility to incorporate and use knowledge and information from a range of decision participants and business functions as well as partner organizations and outside sources. Many PLM decisions need to proceed through stages of

exploration and analysis before final options are considered and may require use of a diversity of tools across these decision stages. The six principles incorporate these requirements. The study uses a research instrument based on the principles and a derived information meta-flow specifying the necessary components for storing decisions as distinct units of knowledge.

The three cases illustrate the flexibility that the principles can provide to support PLM decisions that vary in context, scale and complexity. The cases highlight how the principles can bring formality and rigor to PLM decision-making that may otherwise be ad-hoc and potentially lost to the organization if not recorded explicitly. They also highlight that in combination, the principles allow the flexibility needed in very different application domains. The need for effective support for PLM decision-making is evident in the context of two SMEs and in a large corporation. The exemplar cases highlight that for decision-making in real organizations, formality must be balanced with flexibility to enable problem exploration and learning to occur over the course of a decision problem in order to achieve an appropriate outcome. The six principles support more formalized decision-making across the product lifecycle, facilitating decision retrieval, review, and auditing, which may ultimately lead to organizational learning over time.

Company A needed the recording of the decision process and the outcome, which is valuable for auditing decisions and for future organizational learning from previous decisions. In Company B, the recording of the decision was necessary as the organization operates in a sector where external auditing may be required. Potential decision-making process improvements are evident through communication and the use of decision-making tools. Company C shows the potential for improvements through the adoption of the principles in formalizing the decision-making environment, leading to a more streamlined, focused, and efficient decision-making process, which was a key part of the vision of the organization. Choices are properly recorded along with the rationale that resulted in the choices being made, which may be useful for future decisions. Capturing the decision process and the outcome may act as proof of stakeholder commitments to the decision in the future. In each of the cases, integrating a decision-making process based on the principles within PLM project and process workflows has significant potential. We believe that companies will benefit from (1) recognizing the criticality of decisions and decision making in product lifecycle management processes, (2) adopting a formal approach to decision making in PLM processes based on the six principles, and (3) recording decisions explicitly as distinct units of knowledge in PLM information systems.

Our research instrument was intended as one possible implementation of the decision support principles for research purposes. We did not set out to integrate the research instrument with a PLM project or workflow system but the potential for such integration exists. In particular, we believe the concept of a decision as a distinct unit of PLM knowledge and the six principles and associated meta-data have the potential to be integrated into existing PLM systems, exploiting a number of the typical capabilities of such systems highlighted in section 3.

As with all information systems, PLM systems are subject to continual innovation and change e.g., cloud-based systems, remote access, visibility, connectivity, machine readable knowledge

representations, and artificial intelligence (El Kadiri and Kiritsis 2015; Marra et al. 2018; Singh and Misra 2019). The principles we introduce are strongly relevant to these emerging dispersed and distributed information environments where the need to capture, record, and reuse decisions is even more critical.

PLM systems in the future are likely to offer enhanced capabilities by using and exploiting ontological structures and semantic technologies (McMahon et al. 2004; Blomqvist 2014; El Kadiri and Kiritsis 2015). Ontologies are used to capture models of knowledge in terms of entities and their interrelationships. The use of ontologies implemented within a semantic technology may allow more flexibility in the structure of a knowledge repository designed for decision reuse based on semantic search (Li, Yang and Ramani 2009). Techniques are being developed that use synonyms and related terms to improve information retrieval (Otegi et al. 2014). Appropriately designed ontologies may provide more effective relevance-based search across data and information using different terminology and metadata. We believe the six principles can underpin future ontological structures and reasoning about decisions made in organizational settings by recording content relevant to decision-making processes. Li, Yang and Ramani (2009) note that the definitions of relationships between entities in an ontology provide an important advantage. By structuring the models of decisions as we describe, these relationships may be made more explicit. Appropriate ontological structures and semantic reasoning may further enhance the benefits derived from the six principles to support future PLM systems.

7. Conclusions

The work contributes to the limited research to date on PLM decision-making. The reuse of decisions and decision information is a critical requirement for effective PLM. The paper highlights how group decision support concepts can help to address the requirements for the capturing and reuse of PLM decisions and decision-making processes, contributing to the accumulation of organizational knowledge and organizational learning. The principles presented to support decision-making in a PLM context provide a basis for the effective support of PLM decision-making with significant potential to integrate with existing PLM systems and exploit emerging and future PLM ontologies, which may have wide ranging implications for the PLM processes and protocols of organizations in the future.

The market for PLM systems in 2017 was worth $43.6 billion (Shilovitsky 2018). The topic provides many avenues for further research. We see significant opportunities to research the information needs of PLM decision makers. PLM systems will benefit from improvements that allow decision-making to be supported and decisions made to be recorded, audited, and reused. PLM decision-making environments could be augmented using social software concepts to enhance collaboration (Ullman 2012; Pasley and MacCarthy 2013; Cardon and Marshall 2015), which raises challenging research questions in PLM contexts on the nature of data generated by such software. Given the multi-disciplinary nature of PLM decision-making, past decisions may need to be identified using equivalent, but not identical terms and contexts to those under which they are recorded. Thus, a semantic knowledge base and a semantic approach to search and retrieval of metadata about PLM

decisions may in the future prove beneficial. Work on ontological structures to enhance decision-making in PLM contexts is an exciting avenue for future research.

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