



29th International Conference on Flexible Automation and Intelligent Manufacturing
(FAIM2019), June 24-28, 2019, Limerick, Ireland.

Hidden product knowledge: problems and potential solutions

Lauri Jokinen^{a*}, Simo-Pekka Leino^b

^a*Tampere University, Faculty of Engineering and Natural Sciences, Korkeakoulunkatu 6, FIN-33720, Tampere, Finland*

^b*VTT Technical Research Centre of Finland Ltd, Visiokatu 4, FIN-33720, Tampere, Finland*

Abstract

Requirements and constraints form the base for each new design but in the design phase only a limited amount of them is known; more requirements and constraints appear during the later phases of product lifecycle. At the moment, the information that is collected after the main design phase is not often stored in a re-usable way. On the other hand, large amount of decisions made by design engineers during the design phase is either not stored or documented at all. This lack of lifecycle knowledge causes large amount of unnecessary costs in a form of scrapping, re-work and additional work hours, therefore providing a potential for large savings. This paper explains the current situation, the challenges, the problems and the consequences of poor knowledge management. The problem of hidden product knowledge is a complex one and solving it requires changes to processes, tools, and maybe even to ways certain functions in companies are organized and managed. This paper proposes ways to at least partially solve the problem by using the Product Lifecycle Management (PLM) tools and modifying the way engineers work.

© 2019 The Authors. Published by Elsevier B.V.

This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>)

Peer-review under responsibility of the scientific committee of the Flexible Automation and Intelligent Manufacturing 2019 (FAIM 2019)

Keywords: Knowledge Management; Product Lifecycle Management (PLM); Computer-Aided Design (CAD); Tacit Knowledge; Collaboration; Knowledge Transformation; Engineering Change Management (ECM); Requirements Management; Engineering Tools and Methods; Design Engineering

* Corresponding author. Tel.: +358 445436498.

E-mail address: lauri.jokinen@tuni.fi

1. Introduction

Product development is an iterative process containing the procedures and methods that companies use to design new products from initial ideas and concepts to commercial product and bring them to market [1, 2, 3]. Product design and development transforms [4] high level demanded properties of socio-technical systems into concrete and detailed requirement specifications and design specifications. In other words [5], the subjective demands presented by changing market need to be processed into objective product functions and properties. This transformation is critical but difficult, because the demands often are subjective and in abstract and tacit form [1]. Similarly to market demands that come from customers outside the company, demands also come from stakeholders inside the company. Figure 1 illustrates the process where stakeholder needs are transformed into properties of a technical system.

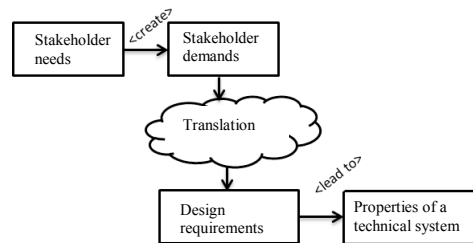


Fig. 1. The connections between needs, demands, requirements and properties (based on ideas by Hubka and Eder in [4]).

The design requirements leave room for different solutions. According to Pahl et al. [6] the optimal solution fulfills requirements and most of the wishes while also being feasible in terms of constraints such as budget and production facilities. This leads to situation where only a limited amount of solutions is chosen and used in the final product. While the final design documents are the most important outputs of the design process, a significantly larger amount of knowledge is generated. Most of this knowledge is not stored in efficient and re-usable way: when the final design documents are published the decisions made by individual people are mostly inside their minds while the documents portray only the chosen solutions. In some fields of engineering, such as mechanical engineering, most documents do not explain in words how mechanisms work – much is expected to be self-explanatory.

The idea of documenting what a designer does is not by itself complicated but in practice, there are severe challenges and this paper does not interfere with all of them. This paper concentrates on the product knowledge that is hidden (or sometimes lost) and seeks answers to following questions:

- What is hidden product knowledge?
- What are the consequences when product knowledge is hidden or missing?
- How to make the hidden product knowledge visible with Product Lifecycle Management (PLM) tools?
 - What kind of impacts would such change have?

2. The research

This research is based on the material collected during three different research projects, spanning eight-year period and involving several companies and several product development projects. Research material consists of case studies, interviews, and notes as well as e-mails and PLM data. The research method is qualitative and descriptive (describing current industrial problems) as well as constructive and prescriptive (suggesting a practical solution) based on action research approach [7] and a pilot solution in the case company.

The research material was analysed systematically using methods such as Ishikawa's cause and effect method [8] and reflected with current literature. The paper tells about root-causes and solutions are suggested. Additionally, this paper introduces a theoretical framework and proposes more detailed research problems as a basis for further research as a part of doctoral dissertation.

3. A short literature review and research gaps

According to Ameri and Dutta [9], in many businesses even 60% of total operational time is waste, i.e. work that does not add value to a product or process. Major proportion of that waste is caused by a lack of efficient knowledge management (KM) that shows as inability to share information and learn from mistakes (for example the ones made in other projects). This leads to poor product development efficiency [3, 9]. Unnecessary engineering changes, re-design and manufacturing scrap are forms of waste in terms of Lean philosophy [10], and design uncertainty is one of the causes.

Uncertainty means “not knowing for sure”, and is caused by a lack of information, ambiguity of existing information [11], or the lack of understanding how different actors interplay with each other (loosely interpreted from [6]). Wynn et al. [12] explain uncertainty as “lack of definition, lack of knowledge, or lack of trust in knowledge”. They [12] continue that reducing the uncertainty is one of the objectives of iterative design process during which information is shared by process participants. Wynn et al. [12] also point out that in the beginning many activities are based on assumptions and much of the knowledge used in the design process is never documented or made explicit. Similar problem of design uncertainty has also been recognized in later phases of lifecycle: Lee et al. [13] claim that as the engineering change management (ECM) systems only store a minimal knowledge of engineering changes (the problems and the solutions but not everything that takes place in the middle), the engineers rely largely on tacit knowledge and off-line communications when making changes to design.

The uncertainty in design phase causes bad decisions that in turn lead to engineering changes in later lifecycle phases [14]. According to Fleche et al. [15], most engineering change requests arise because stakeholders’ knowledge has not been integrated into the product development. On the other hand, Hollauer et al. [14] comment that failing to learn from past engineering changes causes repeated mistakes, unused potential for savings, lack of knowledge re-use for new products, and increased dependability on individual persons. The lack of knowledge integration has also been noted by CIMdata PLM experts [16], according to whom even 95% of time spent for searching and validating information could be cut, thereby increasing productivity of engineers tremendously.

The problem of making design decisions with minimal information has also been mentioned by Simon [17], who comments that the design decisions could be recorded and later viewed from several viewpoints that differ from the ones that generated them. Simon [18] sees new product development as a classical organizational problem of gathering necessary knowledge that originates in many parts of the organization as well as from other stakeholders. This view is also supported by Nonaka and Takeuchi [19], who claim that the knowledge often does exist in the organization, but it is not in the usable form before it is shared and interpreted.

Furthermore, the design decisions are typically spread over time [20] because all parts of a system are not specified and constructed at the same time within common organizational, geographical and cultural settings.

Because there is a need for usable communication medium – to help with the issues mentioned above – it has been suggested [21] that this role could be taken by product models which have traditionally been used for pure information description. However, there is a gap in current literature on how the knowledge management and collaboration should be organized in practice, in complex industrial settings, taking into account whole product lifecycle issues. This paper contributes to research by a) reflecting practical case studies with the literature, and b) by prescribing a practical solution that is explained with the theoretical framework.

4. The Problems

Uncertainty and poor knowledge management reveal themselves in a number of ways. We have chosen five problems that are related to knowledge management and cause uncertainty to product knowledge stakeholders during the product lifecycle. Problems 3 and 4 were first recognized in a project where new design review methods were being tested. In another project, Problems 1 and 2 were recognized (along Problems 3 and 4) when a root cause analysis was performed on a collection of issues related to knowledge management in a case company. Problem 5 was recognized (as well as problems 2, 3 and 4) when analyzing interview material in a project that focused on the relationship between ECM and information quality.

4.1. Problem 1: Requirement formation is front-focused

Whenever a new product development project is started in any company, a list of requirements for the product is formed. The list is, naturally, based on the knowledge (about demands) available at that time. These requirements act as a starting point and guidelines for the design.

However, in addition to original requirements (based on originally formed list of demands), new demands arise after the first designs are released in form of documents. As Pahl et al. [6] and Simon [17] point out, usually the requirements are not constant; they change over time and should be under continuous revision.

Issues are raised in design review meetings [22], and these issues lead to demands that cause changes in designs [23]. Sometimes these changes should lead to changed requirements – not only for this individual design but also for other future designs.

Later, more issues that should lead to new/changed requirements are raised by other stakeholders, such as part manufacturing, assembly line, procurement, and product testing. Their requests could relate for example to manufacturing tolerances, performance, symmetry, modularity, assembly constraints, or safety.

It is practically impossible that the requirements would not change after the initial design phase – this would require a product that is very similar to earlier products, which is not often the case with complex new products. Almost certainly, there will be at least one new part that requires new manufacturing/assembly methods, new tools, or something that should cause the formation of a requirement (see Figure 2).

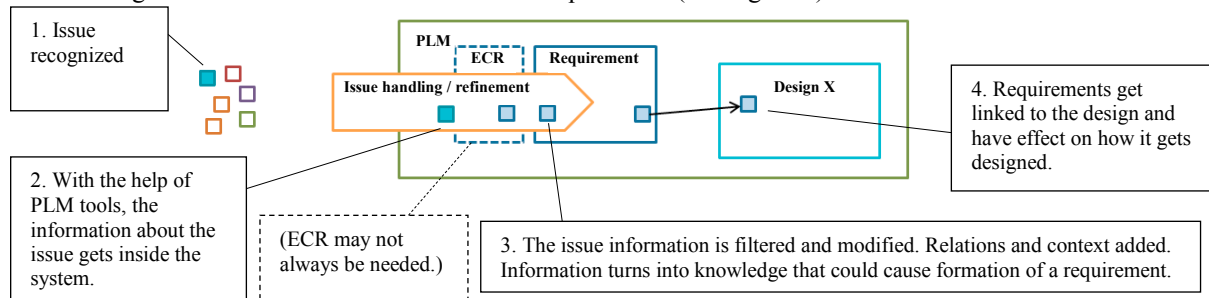


Fig. 2. How tacit (in this case an issue) information should transform into a linked requirement.

Because the issues found later in the lifecycle do not usually form new requirements, the knowledge cannot be reused. Therefore, each project makes same mistakes which, in turn, lead to large number of ECRs that are exceedingly similar to each other. An ECR by itself is a valid documentation of an issue, but an ECR is usually specific and linked to an existing item – it cannot be linked to an item that does not even exist yet. Thus, an ECR alone does not help to prevent future issues (see Figure 3). Preventing future issues would be important, because each accepted ECR starts a costly pipeline that has effect on large number of stakeholders. A single change can quite easily cost a company from thousands to hundreds of thousands (euros/dollars), depending on many factors, but most importantly on how late in the process the change is made [24].

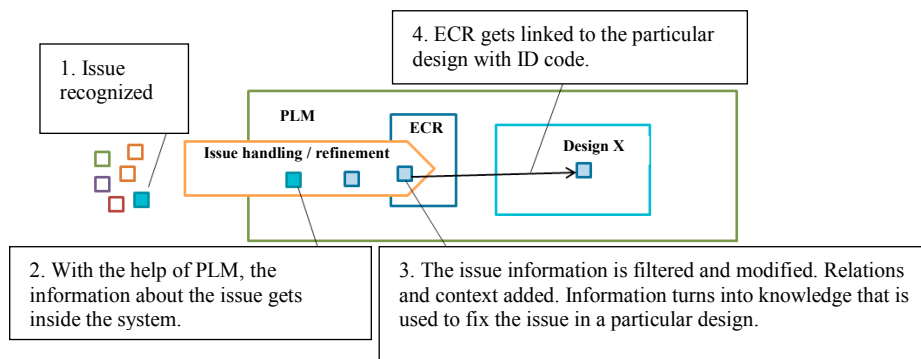


Fig. 3. When an issue is handled as an ECR, but no requirements are formed.

However, ECRs and requirements store only a limited amount of information - even before the later lifecycle phases are involved, a massive amount of knowledge is lost – This leads us to our next point:

4.2. Problem 2: Engineering decisions are not stored

When generating a solution, the design engineer usually goes through several options, at least in his/her mind (see Figure 4, left). Some solutions are rejected immediately as they do not work. Other solutions may work but cannot be used. The engineer finds him/herself in a situation such as the one illustrated in Figure 4 (right).

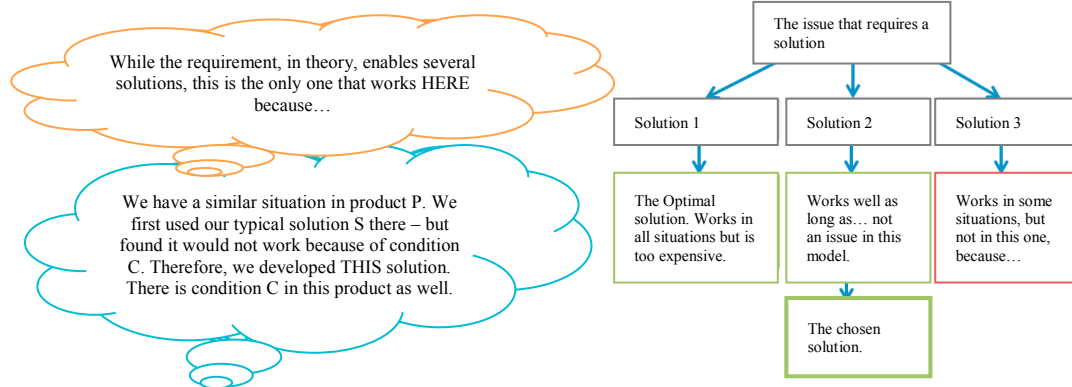


Fig. 4. Left: Examples of thoughts that a design engineer may have in his/her mind. These thoughts may lead to usable solutions. Right: Out of many solutions, only the best one is chosen. The unused solutions, reasoning, and decisions do not get stored in a usable way.

The situation in Figure 4 (right) is problematic, because the best solution could be too expensive for one product but still good for other products. If all these thoughts were documented clearly, maybe someone involved with the design could see them and remember and use the knowledge later in other projects. Now the refined knowledge – that has already cost money and time for the company – is possibly lost entirely.

On the other hand, when people move from one project to another, new person still needs to learn the history of the project. Usually the current design (3D model) represents only the current state and does not explain how and why the end result became what it is. When entering a product development project in the middle – or modifying existing designs – knowing how to use the tools to create and modify 3D parts on computer screen is not enough. There are several reasons behind each existing design decision. Large amount of these decisions may be inherited from earlier designs or otherwise based on experience of product knowledge stakeholders.

In addition to design engineers, the information would be also useful for other stakeholders, for whom it is not always clear why a certain solution was chosen. For example, from spare part perspective it would seem wise to use the same parts as much as possible but sometimes there could be a non-self-evident risk if one otherwise fitting part is used instead of another quite similar looking one. Having access to design decisions (“part made of special material - the normal part cannot be used here because the temperature levels are unusually high”) could be very useful to avoid mistakes caused by uncertainty.

4.3. Problem 3: Links break and the information is lost

Production line is one of the main sources of Engineering Change Requests (ECRs) [25]. In one case company, the largest single source of change requests is usually the final assembly line. However, not always the requestor understands the design decisions and the reasons behind them, which leads to rejections of those ECRs. The rejected ECRs and the reasons for their rejections are available in the Engineering Change Management (ECM) system. However, if a design is copied or modified, the link between the ECR and the design may disappear, for example because of the change in ID codes related to items.

There have been cases where the same change request has been made twice, and the first request has been rejected but the second request has been accepted although it should have been rejected for the same basis as the

original request. This has led to unnecessary back-and-forth changes in the design: a change based on the second ECR is executed, then someone realizes that the new design does not work (just as the engineer handling the first ECR had already realized), and in the end the design is once again changed – usually in a haste and back to the original design. Such changes cause waste of resources and frustration among the engineers as well as assembly workers, purchasers, part manufacturers, and other stakeholders.

4.4. Problem 4: Knowledge is not easily available

Sometimes the knowledge is available, but it is not available as easily as it should. The trouble caused by finding the knowledge leads to knowledge not being searched. Or maybe the need for the knowledge is not even realized. Some important knowledge –for example when related to safety – should be pushed to people. For example, it is possible for an engineer to modify an item that belongs to a module (for example, a hatch)– without even realizing that there is a safety mechanism (for example, a proximity sensor) that also needs modification because of the modification that is performed to another item. There may be a linked document (such as a manual for proximity sensor) telling this, but it is not easy to understand that the change under work has anything to do with the document. It is a good practice to review safety features whenever there are changes, but when the issues are raised late in reviews, it is already more expensive to solve them than if the issue did not exist in the first place.

4.5. Problem 5: Knowledge is not available anymore

The companies with long-serving senior employees seem to rely on these senior employees [26, 27] for example on complicated matters and with issues related to older designs. When these long-serving employees retire or change to another position, the part of their knowledge that was not collected and stored is not available anymore. Although the effect is larger when experienced employee leaves, the problem applies to all employees: the greater the turnover of personnel is in a company, the greater the impact is on the long-term organizational memory [18].

Similar thing may happen whenever a KM related system (PDM/PLM/ERP/ or maybe even a network drive or cloud storage) is changed to a new one – and for one reason or another, the migration is not done properly.

This problem is strongly tied to trusting in tacit knowledge and other unlinked information (such as unmanaged and unlinked files on network drives) – if the knowledge is not properly collected and stored, it will only be accessible for a very limited time.

5. Suggested solutions

There is no single solution that could solve all the problems mentioned in this paper. Nonetheless, there are solutions that would certainly help.

- **Constantly updated requirements base that spans the whole lifecycle.** The demands from stakeholders at later lifecycle phases should be handled in a similar manner to those that are collected in the beginning of the project (i.e. demands at later lifecycle phases should also form requirements).
- **Model-based-definition approach (MBD) & comments.** There should be a layer for comments that the design engineers could use (similar to what programmers do). A possibility to write comments has been available in CAD/PDM/PLM tools for a long time but it is more often used to write instructions to machinists, even though according to Quintana et al. [28], it is still more common to give the instructions in a form of drawing. Commenting the design decisions, interfaces, etc. should be a common practice in engineering design, just as it is in some other domains (such as programming) – and certainly that is not the situation at the moment. The idea of using PMI (*Product and Manufacturing Information* - A format used by certain CAD systems to enable floating text in 3D models) to convey the design intent has been proposed for new product development by Alducin-Quintero et al. [29].
- **Linked information approach.** The design documents (requirements, ECRs, review meeting memos/feedback documents, etc.) should be linked to PLM objects in a way that by clicking any 3D object it is easy to see what documents point to it. Currently, some documents are linked to designs, but often the majority of documents is

still located in shared folders and external systems that are out of reach for the system that stores the actual 3D data. And even the documents that are actually linked to the 3d model may not be easy and intuitive to find – and will therefore opened only when absolutely necessary.

- **Stronger categorization of PLM objects.** The PLM objects should be categorized in many ways, so that some of the documents could be automatically linked to all objects that belong to certain categories.

OR

Inherited object-based approach in PLM. Some of the documents could be linked to meta-objects (such as “electric cabinet”). All the objects that are inherited from meta-objects would therefore inherit certain documents automatically from their parents.

The idea is that when the objects “belong” (either through categories or inheritance), there are more possibilities for linking documents to multiple instances at the same time. On the other hand, when objects “belong”, it is possible to tell that this new part now “belongs” to certain “family” and automatically get suggestions on how it should be designed – even before drawing a single line. Inherited objects are easier to trace than categorized objects, but the chains of inheritance may also get quite complex. (The idea of inherited objects is explained in several research papers. A good example related to the field of PLM is the one by Matsokis & Kiritsis [30].)

It is clear that these changes are not possible without changes in organization. Management and processes need to be revised in order to support these methods. There is also a reason to believe that all PLM systems do not yet have adequate support to commenting layers, especially from usability perspective (filtering, searching, custom views, etc.)

6. Discussion

6.1. Change causes change

As usual, implementing new pieces of technology and working methods requires changes to processes. Additional linking and commenting should be made as a part of standard design engineer work. Corporate level standards on how this should be done would be needed, and time to different design phases should be allocated accordingly. One challenge is how to define criteria for selection of the knowledge that should be captured and fed back, particularly because no one knows what knowledge may be useful in the future [31].

Starting to write / link comments to designs would change computer aided design (CAD) work more towards the working habits of computer programming, where the documentation embedded inside the source code includes interface documents and how-to-use instructions, but also the non-self-evident design decisions.

In addition to design decision commenting, there could be several other information sources linked to the model: ECRs, requirements, standards, directives, design handbooks etc. This amount of information could make the model unusable unless there was a possibility to hide all the unnecessary information - if one concentrates on standards the other linked information could be hidden. Therefore, the information should be grouped – and each group should have its own layer (or similar mechanism) on the model so that the layers could be turned on and off.

On the other hand, when dealing with large amount of information, using search and filter options are often necessary – and neither one of these works well unless the naming/keyword conventions are standardized. Proper naming of designs also helps to avoid unnecessary commenting: if the part is named “heat shield” instead of “plate”, several questions (“Why aluminum instead of steel?”, “Why is it not painted?”, “What is the function of this?”) are already answered.

Writing the design decisions to model could instantly help the designer, as he /she would have to process each decision more thoroughly. The written comments would also act as reminders of earlier thoughts. The real benefits, however, are in information sharing – and if no one ever writes or views the linked information, no benefits will be gained.

Therefore, serious thought from management perspective should be given, before implementing these methods. Managing organizational knowledge is about creating an environment that fosters the continuous creation, aggregation, use and reuse of both organizational and personal knowledge aiming to new business value [32].

However, different communities inside companies, such as executives, engineers, and operative workers do not really understand each other very well, which can hinder organizational learning [33].

One of the problems mentioned in the paper was the turnover of personnel as it is one of the reasons why knowledge is lost. One way to cope with the situation is to store the knowledge better. This could, for reasons mentioned earlier, be seen as a step towards a better learning culture which, according to Joo [34], increases the commitment of workers therefore decreasing the turnover rate. Thus, effective collecting and storing of knowledge is a self-feeding mechanism: the more you store, more sources of knowledge stay available – whereas poor knowledge management seems to drive the sources of tacit knowledge away, worsening the situation exponentially.

6.2. Scientific and managerial implications

The proposed approach of reducing uncertainty in product development by linking requirements and knowledge to 3D models requires relatively small amount of technical development of PLM and other information management system. Thus, bigger changes are related to new processes, methods and procedures as described in chapter 6.1. This organizational change management is the task of directors and managers, and requires good leadership skills. It is the management practices and communication that make the difference [35].

Additionally, especially concerning the whole product lifecycle and integrated product development, it is important to have a holistic approach in organizational design, cross-functional team integration and change management. Instead of department specific goals management should set the goals and rewarding in order to achieve system-wide outcomes [36] of product design and development projects. Furthermore, according to Swink et al. [37] the behavioral aspects of how the changes are employed are more important than the extent to which they are employed. It is good to notice that the often found barriers for instance between engineering design and manufacturing are caused by personal, cultural, language, physical and organizational differences [38]. Harmonization of these differences is in the core of organizational change management and it is important that all stakeholders are treated equally.

In new product manufacturability, management is role-sensitive, knowledge intensive and process driven [39]. It is the task of management to facilitate these dimensions in order to create shared knowledge and improve the product development effectiveness.

This paper contributes to research of product lifecycle management and uncertainty management in product design and development by discussing the possibility and preconditions of better utilization of 3D product models in linking bi-directional information flow, thus enabling product knowledge creation and sharing. The contribution is rooted in discussion between profound industrial case study and literature. Due to the complex and multidimensional research problem, the theory frame was expanded, and the problem was studied with a holistic approach. Based on the case studies, an approach of using existing PLM systems and 3D product models as product knowledge hub was proposed and reflected with literature. The authors believe that sharing the design decisions and conveying the design intent are some of the PLM key problems at the moment, and ones that should receive more attention now that modern, highly integrated and visual PLM systems are becoming increasingly popular.

Answers to research questions:

- **What is hidden product knowledge?**
 - Hidden product knowledge is knowledge that exists but is not easily available. The knowledge itself is generated when the issues are raised, reported and solved. However, the knowledge cannot be efficiently used because it is left in tacit form, without proper context or linked poorly.
- **What are the consequences when product knowledge is hidden or missing?**
 - The hidden product knowledge causes uncertainty and re-appearance of issues that were already solved. Because of the hidden knowledge, the design work becomes exceedingly time-consuming and expensive. Hidden product knowledge also increases use of wrong solutions while reducing the reuse of usable solutions.
- **How to make the hidden product knowledge visible with Product Lifecycle Management (PLM) tools?**
 - It is possible to make the hidden product knowledge visible by constantly updating the requirements base and commenting design decisions on 3d-models, linking the necessary documents (such as requirements and ECRs) to 3d-models, and using either a complex categorization of objects or object-oriented approach with inheritance.

– **What kind of impacts would such change have?**

- Making the hidden product knowledge visible would require changes to how engineers and their organizations work. The change should lead to overall savings by enabling better understanding of products and design intent among all stakeholders, while increasing the quality of design work and decreasing the number of design changes.

7. Conclusion

Usually, the master design data in PLM systems represents the final state of designs and does not explain how and why the final result became what it is. Engineering design is based on stakeholders' needs, and sub-sequent requirements. The accumulation of the needs and requirements does not stop when the design is released to production. The requirements often leave the door open for several different solutions, and usually only one solution will be chosen. As the engineer designs something, he/she also makes a number of decisions. Also, some requirements and design decisions are inherited from earlier projects. Because only a limited amount of decisions is self-evident and major portion of the rest is not documented, the knowledge either stays hidden (in a tacit form) or is lost. In this paper, the authors suggest solutions that should help in collecting, storing, and sharing that knowledge. Clearly, these solutions are only a good start, but they give a hint about the change that seems necessary. There is no reason why the support for commenting and visual linking of documents would not improve in PLM systems in future. The improvements will open new lines of research related to subject of this paper.

References

- [1] K. T. Ulrich and S. D. Eppinger, *Product Design and Development*, McGraw-Hill, 2012.
- [2] D. Unger and S. Eppinger, "Improving product development process design: a method for managing information flows, risks, and iterations," *Journal of Engineering Design*, vol. 22, no. 10, pp. 689-699, 2011.
- [3] P. Hines, M. Francis and P. Found, "Towards lean product lifecycle management," *Journal of Manufacturing Technology Management*, vol. 17, no. 7, pp. 866-887, 2006.
- [4] V. Hubka and W. E. Eder, *Theory of Technical Systems: A Total Concept Theory for Engineering Design*, 2nd ed., Berlin: Springer-Verlag, 1988.
- [5] H.-Z. Huang and Y.-K. Gu, "Product development process modeling based on information feedback and requirement cooperation," *Concurrent Engineering: Research and Applications*, vol. 14, no. 2, pp. 87-98, 2006.
- [6] G. Pahl, W. Beitz, J. Feldhusen and K. H. Grote, *Engineering Design: A Systematic Approach*, Third Edition ed., Springer-Verlag, 2007.
- [7] L. T. M. Blessing and A. Chakrabarti, *DRM, a Design Research Methodology*, London: Springer-Verlag, 2009.
- [8] K. Ishikawa, *Guide to Quality Control*, 14 ed., Tokyo: Asian Productivity Organization, 1998.
- [9] F. Ameri and D. Dutta, "Product Lifecycle Management: Closing the Knowledge Loops," *Computer-Aided Design & Applications*, vol. 2, no. 5, pp. 577-590, 2005.
- [10] J. P. Womack and D. T. Jones, *Lean Thinking: Banish Waste and Create Wealth in Your Corporation*, 2 ed., Productivity Press, 2003.
- [11] G. Grote, "Adding a strategic edge to human factors/ergonomics: Principles for the management of uncertainty as cornerstones for system design," *Applied Ergonomics*, no. 45, pp. 33-39, 2014.
- [12] D. C. Wynn, K. Grebici and P. J. Clarkson, "Modelling the evolution of uncertainty levels during design," *International Journal on Interactive Design and Manufacturing*, vol. 5, no. 3, pp. 187-202, 2011.
- [13] H. J. Lee, H. J. Ahn, J. W. Kim and S. J. Park, "Capturing and reusing knowledge in engineering change management: A case of automobile development," *Information System Frontiers*, no. 8, pp. 375-394, 2006.
- [14] C. Hollauer, M. Wickel and U. Lindemann, "Learning from Past Changes - Towards a Learning-oriented Engineering Change," *Proceedings of the 2014 IEEE IEEM*, pp. 1081-1085, 2014.
- [15] D. Fleche, J.-B. Bluntzer, M. Mahdjoub and J.-C. Sagot, "First step toward a quantitative approach to evaluate collaborative tools," in *Procedia CIRP 21*, 2014.
- [16] CIMdata, "Systems Engineering: At Teamcenter's Core. CIMdata Commentary.," CIMdata, 2012.
- [17] H. A. Simon, "Problem Forming, Problem Finding, and Problem Solving in Design," *Design and Systems: General applications of methodology*, no. 3, pp. 245-257, 1995.
- [18] H. A. Simon, "Bounded Rationality and Organizational Learning," *Organization Science*, vol. 2, no. 1, pp. 125-134, 1991.
- [19] I. Nonaka and H. Takeuchi, *The Knowledge-creating Company*, New York: Oxford University Press, 1995.
- [20] K. Edwards and P. L. Jensen, "Design of systems for productivity and well being," *Applied Ergonomics*, vol. 45, no. 1, pp. 26-32, 2013.

- [21] L. Horváth and I. Rudas, "Indirect communication between engineers through product model," in *7th International Symposium on Intelligent Systems and Informatics, 2009. SISY '09, 2009*.
- [22] G. Huet, S. Culley, C. McMahon and C. Fortin, "Making sense of engineering design review activities," *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, no. 21, pp. 243-265, 2007.
- [23] S.-P. Leino, Reframing the value of virtual prototyping: Intermediary virtual prototyping – the evolving approach of virtual environments based virtual prototyping in the context of new product development and low volume production, 1 ed., Tampere: VTT, 2015.
- [24] C. Terwiesch and C. H. Loch, "Managing the Process of Engineering Change Orders: The Case of Climate Control System in Automobile Development," *The Journal of Product Innovation Management*, vol. 16, no. 2, pp. 160-172, 1999.
- [25] G. Q. Huang and K. L. Mak, "Current practices of engineering change management in UK manufacturing industries," *International Journal of Operations & Production Management*, vol. 19, no. 1, pp. 21-37, 1999.
- [26] M. Alvesson and D. Kärreman, "Odd couple: Making sense of the curious concept of knowledge management," *Journal of Management Studies*, vol. 38, no. 7, pp. 995-1018, 2001.
- [27] T. Flanagan, C. Eckert and P. J. Clarkson, "Externalizing tacit overview knowledge: A model-based approach to supporting design teams," *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, no. 21, p. 227–242, 2007.
- [28] V. Quintana, L. Rivest, R. Pellerin and F. Kheddouci, "Re-engineering the Engineering Change Management process for a drawing-less environment," *Computers in Industry*, no. 63, pp. 79-90, 2012.
- [29] G. Alducin-Quintero, A. Rojo, F. Plata and A. Hernández, "3D Model Annotation As a Tool for Improving Design Intent Communication: A Case Study On Its Impact In The Engineering Change Process," *Proceedings of the ASME 2012 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference IDETC/CIE 2012 August 12-15, 2012, Chicago, IL, USA, 2012*.
- [30] A. Matsokis and D. Kiritsis, "An ontology-based approach for Product Lifecycle Management," *Computers in Industry*, no. 61, pp. 787-797, 2010.
- [31] E. Marcandella, M.-G. Durand, J. Renaud and V. Boly, "Past projects memory: Knowledge capitalization from the early phases of innovative projects," *Concurrent Engineering: Research and Applications*, vol. 17, no. 3, pp. 213-224, 2009.
- [32] A. Milicic, S. El Kadiri, A. Perdikakis, P. Ivanov and D. Kiritsis, "Toward the definition of domain concepts and knowledge through the application of the user story mapping method," *International Journal of Product Lifecycle Management*, vol. 7, no. 1, pp. 3-16, 2014.
- [33] E. H. Schein, "Three Cultures of Management: The Key to Organizational Learning," *Sloan Management Review*, vol. 38, no. 1, pp. 9-20, 1996.
- [34] B.-K. Joo, "Organizational Commitment for Knowledge Workers: The Roles of Perceived Organizational Learning Culture, Leader–Member Exchange Quality, and Turnover Intention," *Human Resource Development Quarterly*, vol. 21, no. 1, 2010.
- [35] H. Maylor, "Concurrent new product development: an empirical assessment," *International Journal of Operations & Production Management*, vol. 17, no. 12, pp. 1196-1214, 1997.
- [36] X. A. Koufteros, M. A. Vonderembse and W. J. Doll, "Integrated product development practices and competitive capabilities: the effects of uncertainty, equivocality, and platform strategy," *Journal of Operations Management*, vol. 20, no. 4, pp. 331-355, 2002.
- [37] M. Swink, S. Talluri and T. Pandéjpong, "Faster, better, cheaper: A study of NPD project efficiency and performance tradeoffs," *Journal of Operations Management*, vol. 24, no. 5, pp. 542-562, 2006.
- [38] A. Vandeveld and R. Van Dierdonck, "Managing the design-manufacturing interface," *International Journal of Operations & Production Management*, vol. 23, no. 11, pp. 1326 - 1348, 2003.
- [39] W. J. Doll, P. Hong and A. Nahm, "Antecedents and outcomes of manufacturability in integrated product development," *International Journal of Operations & Production Management*, vol. 30, no. 8, pp. 821 - 852, 2010.