Reducing professional maintenance losses in production by efficient knowledge management in machine acquisitions

Malin Hane Hagström, Dag Bergsjö*,
Jonny Blomberg and Martin Håkansson

Chalmers University of Technology,
412 96, Gothenburg, Sweden
Email: hanem@chalmers.se
Email: dagb@chalmers.se
Email: blombergjonny@gmail.com
Email: martin.hakansson08@gmail.com
*Corresponding author

Abstract: Research in product development has shown the importance of reusing knowledge to eliminate future design weaknesses. Previous research has shown that maintenance- and equipment breakdown-related losses are the second and third largest losses in a specific studied automotive flow and that the losses are originating from the design phase. This paper presents a case study performed on four industrial acquisition projects where the case company already had one machine and was buying more machines of the same type. The study focuses on how knowledge about the existing machine is re-used in the new acquisition process. Potential barriers that hinder reusing the engineering knowledge are identified. The main conclusions are that there is a need for increased focus on the importance of knowledge transfer, more emphasis on maturing knowledge, increase the diversity in the engineering teams, ensure the design model is applying lean concepts, and to improve the documentation interface with suppliers.

Keywords: system engineering design; Industry 4.0; design models; knowledge management; lean product development; lean enterprise; professional maintenance; machine acquisitions; early equipment management.

Reference to this paper should be made as follows: Hagström, M.H., Bergsjö, D., Blomberg, J. and Håkansson, M. (2022) 'Reducing professional maintenance losses in production by efficient knowledge management in machine acquisitions', *Int. J. Product Lifecycle Management*, Vol. 14, No. 1, pp.70–101.

Biographical notes: Malin Hane Hagström is an Industrial PhD at the Research Group Systems Engineering Design, since January 2018. Her research focuses on knowledge management between production and product development with a focus on lean principles and continuous improvement. The aim is to find ways to build in production knowledge regarding lean in the equipment acquisition phase with a special focus on professional maintenance.

Dag Bergsjö is a Professor in Systems Engineering Design. He has researched the subject of information and knowledge management in the context of Systems engineering since 2005. He received his PhD in 2009.

Jonny Blomberg performed his Master thesis work at Chalmers University of Technology relating to this study. His Master thesis was titled 'Knowledge Management in the Procurement Process' and was published in 2019.

Martin Håkansson performed his Master thesis work at Chalmers University of Technology relating to this study. His Master thesis was titled 'Knowledge Management in the Procurement Process' and was published in 2019.

1 Introduction

Society is demanding shorter development cycles and increased resource efficiency (Lasi et al., 2014). To meet these expectations, Industry 4.0 has developed to address the next paradigm shift in industry; towards enabling the usage of internet of things and collaborative and proactive solutions (Bokrantz et al., 2017). When in place, the Industry 4.0 factory should have developed into an intelligent environment where the system of production equipment is exchanging information, triggering actions and controlling each other autonomously (Weyerx et al., 2015). It is evident that machines will be performing more complex tasks and require higher uptimes which will put high demands on designing the production system, on acquiring the machines and enable the ability to maintain them. Another paradigm shift is the transfer to circular economy. Circular economy is considered as an innovative approach used to increase the resource efficiency in companies by keeping equipment functioning for as long as possible (Wakiru et al., 2018). This implies that the society needs to become better and better at designing for sustainability which means then designing for maintainability. In the lean philosophy, sustainability is the overall purpose by removing waste and losses and preferably designing the systems to minimise wastes and losses in the production from the start of production, so the lean thinking is a way of thinking that enables sustainability. As stated by grieves, product lifecycle management (PLM), is taking lean to the next level (Grieves, 2006). Traditionally, lean has focus on eliminating waste in the production process, while PLM aims at using digitalised information to be effective and productive throughout the design, development, and delivery process as well. Traditional lean initiatives have also focused the improvement efforts within the production scope, PLM is focusing on driving improvements cross-functionally, including the supply chain to unlock productivity gains that cannot be obtained if the focus is solely on individual areas (Grieves, 2006). PLM strives to increase revenues by three enablers; innovation, functionality and quality, which are obtained by better organisation and utilisation of the intellectual capital in the organisation (Grieves, 2006). To fulfil the vision of PLM (Terzi et al., 2010), the PLM system should span across the entire lifecycle including all engineering efforts in the extended enterprise, hence this paper also aims towards including the purchasing and maintenance of factory equipment, with the same principles as PLM is often used to design and support the company's final products.

Other research has also demonstrated the importance of using knowledge gained from earlier projects to eliminate future design weaknesses (Morgan and Liker, 2006). The involvement of suppliers to reach success in new equipment projects are also emphasised (Petersen et al., 2005). Other studies have shown that maintenance- and equipment breakdown-related losses are second to third largest contributors in automotive flows

(Hane Hagström et al., 2020). This combination makes it relevant to examine how maintenance related knowledge from operations is captured and transferred into the process of procuring new equipment and for the future maintenance needs to be more and more integrated.

This article will study the industrial system as the system of interest, and present findings from four cases where the case company already had one machine and bought another machine of the same type. In theory, previous experiences from running the old machine should affect the buying of the new machine, in order to ensure that problems or errors (with root causes in installation, operation or maintenance) does not occur again. The barriers of how capturing and transferring maintenance related knowledge from operations into the process of procuring new equipment from suppliers is investigated. Of specific focus is the information and knowledge created in the design and purchasing process of the old machinery and how that information and knowledge is used and transferred to the team buying the new machinery. This is a classic PLM challenge of making information and knowledge, transparent, available, and understandable by the future recipient.

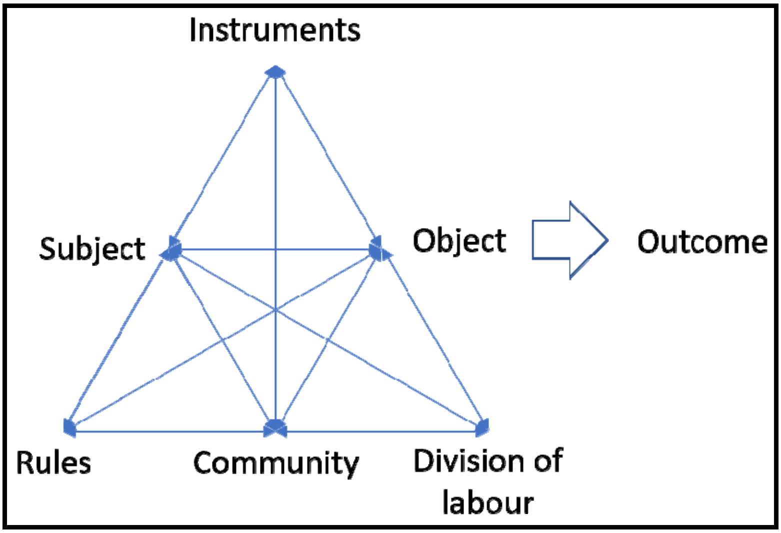
2 Research approach

This paper is a descriptive study, as defined by blessing in the design research methodology (DRM) (Blessing and Chakrabarti, 2009). The research design of this paper is a combination of literature studies (Webster and Watson, 2002) and case studies (Bryman, 2003). The case study data is collected by semi-structured interviews (Denscombe, 2014). The literature study covered the areas of lean thinking, maintenance, knowledge management and early equipment management (machine acquisition). The interviews followed an interview guide (see Appendix), with the main themes of early equipment management, supplier collaboration and knowledge management. For the interviews, key positions in each project were selected, based on the identified roles influencing the quality of maintenance of the machines. Twenty-two interviews were conducted, all in person with the same two persons interviewing, and in average 42 minutes long. The interviews were recorded, transcribed to text and then imported to qualitative data analysis software Nvivo version 12. The analysis of the data was performed by all authors.

The reliability of the data is enhanced by using a pre-set interview guide, developed in the team and also that each interview is performed in pairs, recorded, transcribed and then reviewed by a third person. The validity of the data is enhanced by using senior experts in the business to identify the relevance of the questions and identifying key stakeholders. Finally, to strengthen both the reliability and the validity, triangulation (Mathison, 1988) was used. In this study the qualitative data is complemented with literature study and review of internal documents, which together creates the triangulation.

For analysis, other than the knowledge transfer barriers from Riege, the framework of activity theory for organisational learning is used (Engeström, 2000) as described in Figure 1.

Figure 1 Activity theory for organisational learning (see online version for colours)



Source: Engeström (2000)

Activity theory is a framework for analysing and redesigning work. Engeström (2000) argues that as the work environment changes many traditional boundaries are collapsing and that to be able to do research on concepts such as learning organisations and knowledge management, academia need hybrid models that cut across disciplines, from economics and sociology to cognitive science and ergonomics (Engeström, 2000). The activity theory model is an attempt to capture several of these disciplines in one system theory framework.

3 Frame of reference

Earlier studies by the authors have identified that when analysing automotive flows from a lean perspective, maintenance is one of the major issues (Hane Hagström et al., 2020). As the prerequisites for the production flows are established in the production engineering phase, which is a knowledge-centric activity, this article is based upon the theoretical foundation consisting of four main areas: lean thinking, knowledge management, early equipment management (machine acquisition) and maintenance.

3.1 Lean thinking

Lean has inspired many, various, disciplines in the world to identify waste and losses. Traditionally the focus of lean has been in production flows, but the attention is expanding to look further into other processes such as banking and hospital services but also into engineering flows (Bhasin, 2015). Fundamental lean manufacturing and the philosophy behind it was established by Toyota. The lean principles were termed in the 90's and was derived from the Toyota production system, TPS, where the focus is on eliminating the wastes to elevate the company's overall productivity and customer value (Womack et al., 1990).

According to Womack, Jones et al. (1990), one of the major goals of lean manufacturing is to implement a philosophy of continuous improvement that allows companies to reduce costs, improve processes and eliminate waste to increase customer satisfaction and profit. Lean manufacturing provides companies with the tools to survive in a global market that demands higher quality, faster delivery, and lower prices, at the volumes required to sustain the business. Specifically, its main objectives are to:

a drastically reduce waste in the supply chain

b reduces inventory and space occupied on the production floor

c creates more robust production systems

d create appropriate systems for the delivery of materials

e improves the organisation's production areas in order to increase flexibility, a factor that is growing more and more in importance considering the rapid changes in customer demands (J.R.X. and Alves, 2015).

The lean thinking is relevant for this article in several ways. Firstly, the machines in the production system are key enablers to achieve the main objectives mentioned in the section above. Secondly, the acquisition of the machines is part of the designing of the production system, meaning that the design process in itself could also be subject to lean thinking, lean design. Traditional product development models usually lead to a number of problems commonly seen in companies; some of them are:

1 work overload on designers and engineers that frequently perform unnecessary tasks,

2 a model that is not clearly understood by designers

3 project cost overruns

4 difficulties in retrieving knowledge from previous projects

5 ambiguities regarding tasks' responsibilities due to insufficient commitment of functional departments (Tortorella et al., 2016).

When applying the lean philosophy in design the main principles are the same, but the application differs. There have been many efforts to define more precisely what lean product development is (Tortorella, et al., 2016) and several definitions exist. One definition is stated by Ward (2007) that

> "Lean product development is as a set of operational value streams that should be designed to consistently execute product development activities effectively and efficiently, creating usable knowledge through learning. The building blocks of such value streams and knowledge creation cycle are organised in five principles: value focus, entrepreneurial system designer, teams of responsible experts, set-based concurrent engineering and cadence (pull and flow)."

The term 'usable knowledge' is defined as the value adding part of lean product development.

This means that for the design of the production system, it is critical to focus on the knowledge creation in the design process to enable the production system to support the lean principles of production.

3.2 Knowledge management

Knowledge can be described as a pyramid consisting of data as the base, then information and finally knowledge where the amount of structure and context is increasing as you move up in the structure (Alavi and Leidner, 2001). Numbers, letters, and pictures and often referred to as data. Information can be described as data in context. Knowledge demands an understanding of a given situation and the context to such a degree that it is possible to identify leverage points and weaknesses; in short a more meaningful awareness and understanding (Stenholm, 2018).

There are three major knowledge categories: individual, global and organisational knowledge (Tryon Jr, 2016). The individual knowledge can be described as the mix of both formal education and personal experiences. Global knowledge is knowledge that can be found in e.g., textbooks, internet, or databases. Organisational knowledge is defined as "the knowing required by an enterprise to produce the products and services necessary to perform the work of the enterprise." This knowledge is unique for the organisation and is built upon all employees' knowledge creation, development, and transfer. Organisational knowledge can be divided in three sub-groups:

- Explicit knowledge is knowledge that easily can be transmitted to others in form of e.g., written content, audio- and/or video recordings.
- Implicit knowledge is knowledge that could become explicit but at the particular moment of interest, for various reasons, is not.
- Tacit knowledge is knowledge that is difficult to transfer through words or physical media. By some it is referred to as intuition or judgement, for example riding a bike.

Engineering is a knowledge-centric activity (Natarajan et al., 2019). Natarajan et al. (2019) mentions that

> "As engineers, we manage complexity operationally by using our (partly tacit) understanding by crating overall system models, multiple domain-specific models and views and maintaining and managing consistency among all of them."

This means, for effective system engineering design managing knowledge is key. Knowledge management can be seen as a knowledge-creating activity with the purpose of frequent and structured knowledge re-use (Stenholm, 2018). To enable the organisational learning and re-use of knowledge continuously and not only focus on the knowledge project by project, but it is also important to feed the so called knowledge value stream in the organisation which builds the knowledge from all projects and advanced engineering efforts (Kennedy, 2008). For effective systems support, IT for knowledge management is commonly referred to as knowledge management systems (Lehner and Maier, 2000). A short and condensed knowledge management system format is essential to eliminate unnecessary activities and to ensure the applicability of the latest knowledge (Stenholm, 2018). Many organisations use knowledge reuse support such as Blogs, Wikis or checklists (Bergsjö et al., 2021). Studies show that the support tools used should cover three aspects to be most effective:

- Know-what: Actions/decisions that needs to be taken/made?
- Know-why: Why does this specific action/ decision need to be made. Why is it important?
- Know-how: How will the action/decision preferably be performed? What is important to keep in mind/consider?

Re-using knowledge is one of the core parts in the industrial system design engineering process, and more specifically of procuring production equipment. Studies show that managing knowledge is also of great importance when collaborating with suppliers in order to achieve a robust equipment (Bellgran and Säfsten, 2010).

Wynn and Clarkson (2018) have in an extensive manor described various types of product development models and have on a high-level described them as either procedural, analytical, abstract or management science/operations research models:

- procedural models convey best practices intended to guide real-world situations
- analytical models provide situation-specific insight, improvement and/or support which is based on representing the details of a particular design and development instance
- abstract models convey theories and conceptual insights regarding the design and development process
- management science/operations research models use mathematical or computational analysis of representative or synthetic cases to develop generally applicable insight into design and development.

Further on, the models are categorised as operating on either micro – meso – or macro level:

- micro-level models focus on individual process steps and their immediate contexts
- meso-level models focus on end-to-end flows of tasks as the design is progressed
- macro-level models focus on project structures and/or the design process in a context.

The study states that knowledge management models are predominantly in the micro-level analytical model, meaning focusing on the individual process steps and their immediate contexts which provides situation-specific insights, improvement and/or support based in representing the details of a particular design and development instance.

Studies have shown that several barriers exist (Table 1) for efficient knowledge sharing activities (Riege 2005). For efficient knowledge sharing, these barriers must be identified and addressed.

Table 1 Barriers for knowledge sharing

Individual	
IB1	General lack of time to share knowledge and time to identify colleagues in need of specific knowledge
IB2	Apprehension for fear that sharing may reduce or jeopardise people's job security
IB3	Low awareness and realisation of the value and benefit of possessed knowledge to others
IB4	Dominance of sharing explicit over tacit knowledge, such as know-how and experience that requires hands-on learning, observation, dialogue and interactive problem-solving
IB5	Use of strong hierarchy, position-based status and formal power
IB6	Insufficient knowledge capture, evaluation, feedback, communication and tolerance of past mistakes that would enhance individual and organisational learning effects
IB7	Difference in experience levels
IB8	Lack of contact tome and interaction between knowledge sources and recipients
IB9	Poor verbal / written communication and interpersonal skills
IB10	Age differences
IB11	Gender differences
IB12	Lack of social network
IB13	Differences in education levels
IB14	Taking ownership of intellectual property due to fear of not receiving fair recognition and accreditation from managers and colleagues
IB15	Lack of trust in people because they may misuse or take unjust credit of the knowledge
IB16	Lack of trust in accuracy and credibility of knowledge
IB17	Differences in national culture or ethnic background; and values and beliefs associated with it (language is part of this)
Organisational	
OB1	Missing or unclear integration of knowledge reuse into the company's goals and strategy
OB2	Lack of practices, leadership and managerial direction that clearly communicates the benefits and values for knowledge sharing practices
OB3	Shortage of formal/informal spaces for share, reflect and generate (new) knowledge
OB4	Lack of a transparent reward and recognition system that would motivate people to share more of their knowledge
OB5	Existing corporate culture is not providing sufficient support for sharing practices
OB6	Knowledge retention of highly skilled and experienced staff is not a high priority
OB7	Shortage of appropriate infrastructure supporting sharing practices
OB8	Deficiency of company resources that would provide adequate sharing opportunities
OB9	High external competitiveness within business units or functional areas and between subsidiaries (not-invented-here syndrome)
OB10	Flows of knowledge and communication are restricted into certain directions (e.g., top-down)
OB11	Physical work environment and layout of work areas restrict effective sharing practices
OB12	High internal competitiveness within business units or functional areas and between subsidiaries (not-invented-here syndrome)
OB13	Hierarchical organisation structure inhibits or slows down most sharing practices
OB14	Size of business unit often not small or manageable enough to enhance contact and facilitate ease of sharing

Source: Riege (2005)

Table 1 Barriers for knowledge sharing (continued)

Technology	
T1	Lack of IT systems and processes impedes the way people do things
T2	Lack of technical support (internal or external) and immediate maintenance of integrated IT systems obstruct work routines and communication flows
T3	Unrealistic expectations of employees as to what technology can do and cannot do
T4	Lack of compatibility between IT systems and processes
T5	Mismatch between the needs and requirements of individuals and integrated IT systems and processes
T6	Reluctance to use IT systems due to lack of familiarity and experience with them
T7	Lack of training regarding employee familiarisation with new IT systems and processes
T8	Lack of communication and demonstration of all advantages of potential new systems over existing ones

Source: Riege (2005)

3.3 Early equipment management (machine acquisition)

The process of investing in new production equipment is at the case company called early equipment management (EEM). There are various reasons why a company would like to invest in new machines; it could be to increase capacity, replacement, or introduction of new products that the current equipment is not capable of producing. Equipment acquisition in this definition concerns machines that are not bought off the shelf but are instead designed to order, leading to longer lead times and higher procurement cost (Yeo and Ning, 2006). To meet this challenge in product development, a well-developed collaboration between supplier and buyer is advocated (Hoegl and Wagner, 2005).

Equipment investments are usually conducted in projects, which entails project metrics as time and cost (Jha and Iyer, 2007). EEM, however, is not only about the investment but rather to procure the best possible equipment by using existing knowledge and experience. To make sure the adequate knowledge is available for ongoing projects, several activities need to take place outside of the project environment (Stenholm, 2018). Knowledge should be collected from several parts of the organisation and be fed into the procurement process to ensure the best equipment is purchased from several angles of operations.

Maintenance has been found to be a major contributor to achieve equipment stability and is one of the success factors in EEM (Gulati, 2013). Several production disturbances are often experienced after implementing a new machine; difficulties in maintainability, complex equipment, safety issues and difficulties to achieve high efficiency from start of production. It is by identifying the root cause for these potential future disturbances already in the development phase that they can be eliminated (Gullander et al., 2005; Bellgran and Säfsten, 2010; Gulati, 2013).

3.4 Maintenance

The Swedish Standards Institute describes maintenance as “the combination of technical and administrative actions, including monitoring, intended to maintain or restore a device to such a state that it can perform a required function” (SIS, 2000). Further on, Gulati describes maintenance as the work of keeping the condition of the production equipment so that it can achieve its intended production efficiency (Gulati, 2013). Events that disturb the intended production condition can be regarded as disturbances and losses for production. The activities in maintenance are both activities that prevent failures of the equipment but also activities that restores the condition into the original condition. All maintenance activities have the target of maximising production capacity and reducing overall costs of the production (Bellgran and Säfsten, 2010).

The maintenance cost increases nearly exponentially closer to the end of the equipment's life cycle and it is in the design stage that it is possible to prevent many of the causes for production disturbances in a cost efficient way (Bellgran and Säfsten, 2010; Gulati, 2013). Despite the potential in cost savings, studies show that the awareness of the cost implied with breakdowns and maintenance losses is low among respondents in Swedish industry (Salonen and Tabikh, 2016). Other studies show that even though the importance of maintenance have been acknowledged, industry under performs due to under investments in the maintenance organisations (Lundgren, 2019).

Lundgren further mentions that it is important to link the maintenance cost and potential production disturbances already in the procurement process. This is also supported by Salonen, (2018), who showed that 65% of recorded data from eight automotive sites in Sweden registered design weakness of the machine as the root cause of the breakdowns. In addition, 23% of the breakdowns was related to poor professional maintenance performed. The article also mentions that there is a missing area of research on how to manage the procurement and/or design of dependable production equipment, which further highlights the research gap this article is covering.

4 Case study

The studied case company is a global actor in the transport solution business with about 100, 000 employees world-wide. Several brands are represented in the portfolio and a variety of vehicles, from excavators to buses and trucks. The company is set up by several organisations who are all interacting on operational level. The company has factories in 18 countries. In addition to the production sites the industrial operations include development centres. Four cases of procuring additional machines of which the organisation was already running machines of the same type were selected. Two cases were finished and two are still ongoing. Figure 2 describes the nature of the projects:

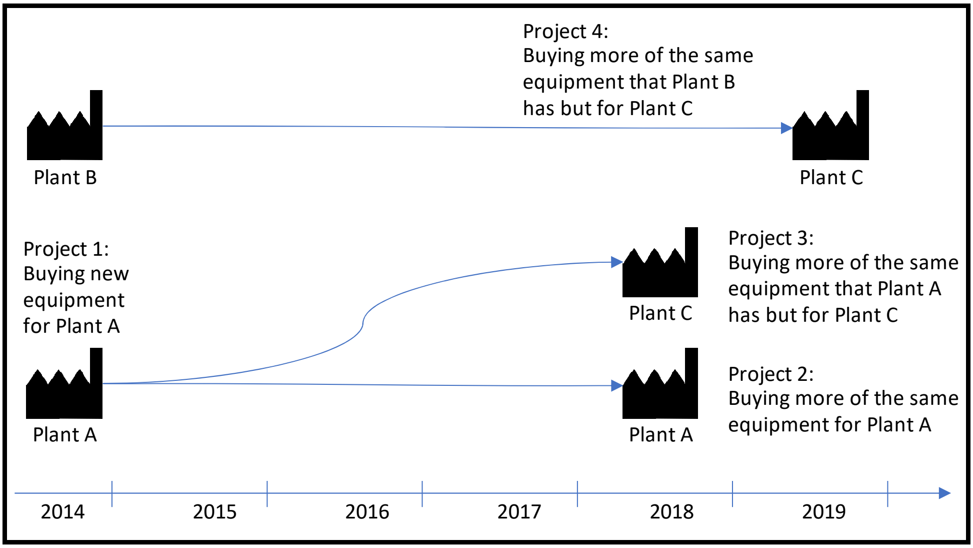
Project 1 Buy new equipment for plant a – completed

Project 2 Buy more of the same equipment for plant a – completed

Project 3 Buying more of the same equipment that plant a has but for plant C – ongoing

Project 4 Buying more of the same equipment that plant b has but for plant C – ongoing

Figure 2 Overview of the studied equipment acquisition projects (see online version for colours)



4.1 Data collection

The four projects were selected from the business as intense knowledge transfer cases with high complexity and scale of cost. An emphasis is put on maintenance and the management activities in the project. The purchasing/supplier side and the operators are key future users. Table 2 shows the interviewees roles at each plant.

Table 2 Overview of interviewees per plant and per role

Function	*Plant A*	*Plant B*	*Plant C*	*External*
Process leader	I1		I13 + I14	I20
Process owner		I7 + I8		
Maintenance manager		I9	I15	I21
Mechanical maintenance	I2 + I3	I10	I16	
Electrical maintenance	I4	I11	I17	
Purchasing	I5	I12	I18	
Operator	I6		I19	

5 Results

5.1 Definition, objectives, and challenges of EEM from a maintenance perspective

In the following text the summary of the interviewees at the different plants are presented. For further detail, refer to Appendix Table A1.

5.1.1 Definition of EEM

In plant A, EEM was defined as being a structured framework for procuring equipment by using previous experience. Three of the interviewees mention that EEM is a process where lessons learned from previous projects are to be included. All of them describe EEM as a structured process for procuring equipment. As one interviewee states it: "It is a good framework to tell you what do and when. It is a way of working that I think works quite well." In plant B, EEM was defined as structured framework to get improvements in the new equipment. Also, all of them describe it as a structured process for procuring equipment. Only one interviewee stated that working with EEM was a possibility for inputs of improvements. "For me, the principle of EEM is that when we are in the process of buying a new machine, we look at previous projects for any improvement points we can incorporate in this purchase." In plant C, EEM was defined as a structured framework for procuring equipment with highest possible up-time, by involvement of different functions. Only one interviewee described EEM as being a process with focus on longevity, "the philosophy is to find out how to maintain your equipment with the highest level of uptime possible and minimising the downtime, that is what EEM truly is." The interviewee also expressed a concern of the lack of understanding of the EEM philosophy among the colleagues.

> "Most people don't understand EEM; most people believe more in the old form of preventive maintenance when you set a schedule for tasks and that is it. Now we are in a more competitive situation and we need to be able to get as much available time as possible for production."

5.1.2 Objective of EEM

Plant A focuses on satisfying the production department, referred to as the customer, by delivering better equipment. Indicators as 'reliability' and 'availability' are often mentioned as measurements for better equipment. One project manager stated specifically that "the project should meet the targets in terms of cost and performance but also other values such as environmental, safety and ergonomic aspects." Plant C mentions that the objective of EEM is to include all the departments different requirements, as well as delivering better equipment. The electric maintenance technician defines better equipment as having more up-time and less down-time. Plant B is instead focusing on delivering equipment without disturbances that produce in line with expectations, aspects as knowing what do to and minimising risk is also mentioned. One interviewee stated that the objective is that the equipment is performing better, as a result from the invested time in making sure that the project has captured all knowledge and experience. One interesting observation is that all interviewees mention the specific project as the objective; not the success of all projects from a systemic view, which is in the theory defined as the organisational knowledge value stream.

5.1.3 Challenges in EEM

All three plants find the high workload or limited amount of time challenging. Plant B find the lack of resources and competence restricting. As one interview mentions, "we have the processes described very well but the trigger to buy a machine is very often too late which means the entire purchase is stressed." Another insightful comment was "this was very frustrating in the beginning but as I learn more, I realise how difficult it is for everyone to take the necessary decisions in time." Plant A also finds competence a challenge, specifically how to know what competence to include into the project to achieve success. "The main challenge is to have a clear specification from the requester and that the requester has the competence to know what he or she needs, which is sometimes not the case." Regarding the time aspect, one person from Plant A states that "we are rather conservative as we do not have time to test new technologies or new suppliers always." The softer aspects are also mentioned. "To make a successful project you need not only competence but also engagement and commitment from the people involved." Individuals of plant C find it difficult with the high workload and making other people in the organisation to understand the philosophy. A maintenance representative describes one of the main challenges:

> "So if you build a better house it last longer so most people have a job to do. Project managers have to be on time and under budget, that is their philosophy. But that kind of collides in the holistic view, it is kind of colliding with trying to make this the best machine possible."

The interviewee describes the main challenge being the campaigning, making other understanding the philosophy. The interviewee also describes the conflict between the traditional view on a project, time, and budget, with the holistic view of EEM.

5.2 Knowledge management in EEM

In Appendix Table A2, the interviewees' statements are summarised. The barriers are mapped towards the criteria's defined by Riege (2005).

Several process tools are used as to do-lists, to secure that the right knowledge is brought into the project. Most of the interviewees describe how they also perform other activities such as study visits, benchmarks and training in addition to the stated process. Involvement of operators, maintenance and technicians is seen by engaging these through interviews and the creation of a list of improvements. Several of the interviewees describe a lack of knowledge in EEM and the process of capturing knowledge and experience. It is mentioned that the level of knowledge has decreased past years and that it is difficult to find the appropriate knowledge.

The tools and methods that are used today for capture, share and re-use knowledge are:

- *Emergency work order*: this is a pre-set template for when machine breakdowns occur. It guides the maintenance technician to describe the problem, identify the root cause and suggests solutions based on the root cause. This tool is used on close to all breakdowns.
- *Human error root cause analysis (HERCA)*: if the problem-solving activity points to the root cause being a human error, the human error root cause analysis (HERCA) guides the team to find the proper countermeasure. This tool is used on close to all errors classified as human errors.
- *White book:* this is performed after a machine acquisition project is closed to capture lessons learned. These are not always done or studied.

- *Industrial project assurance plan*: is a document with checkpoints that should be achieved for each gate. This is frequently used for projects that are significant in size to be classified as EEM projects.
- *Technical specification*: a detailed document with all requirements specified.
- *Scope of supply*: defines in detail what the supplier is supposed to deliver.
- *Operator's list:* in this case an individual initiative from an operator to capture knowledge from colleagues.
- *Benchmark*: a systematic visit to other companies who are using the same machines.
- *Study visit:* a systematic visit to sister plants within the company
- *Training*: a systematic approach from supplier to the case company

Table 3 shows the methods that are used to capture knowledge today as input for the EEM process and what type of knowledge they capture.

Table 3 Tools that are used in the case company to capture and transfer knowledge

Tool	*Knowledge type*	*Plant A*	*Plant B*	*Plant C*
Emergency work order (EWO)	Explicit	X	X	X
Human error root cause analysis (HERCA)	Explicit			X
White book	Explicit		X	X
Industrial project assurance plan (IPAP)	Explicit	X		
Technical specification	Explicit		X	
Scope of supply	Explicit	X	X	
Operators' list	Explicit	X		
Benchmark	Implicit	X		X
Study visit	Tacit	X	X	
Training	Tacit	X	X	X

Regarding the barriers from effective knowledge management, specifically a few aspects were mentioned. For example, on the organisational level, when asked how knowledge is captured for the next machine to be bought, one respondent stated "there is no way to capture this, other than me saying to my colleague that that drive is horrible. If we ever buy this machine again it would just be me verbally saying something." Others mention that there is more from an individual basis that people express a willingness to learn rather than a systematic approach from the organisation. "We asked for volunteers among some of the younger engineers if they wanted to shadow the process."

From the technological point of view, it is mentioned that the systems are perhaps not built up in the most useful way for the engineers: "today we have all requirements in one system; it would be beneficial to have one requirement list for maintenance, one for safety, one for quality etc." Another example from the technological view is regarding documentation: "we received the information too late and when we received it, we discovered that is was sorted in the wrong structure."

From the organisational perspective again one interviewee mentions that "15 years ago we had more skilled people than we have today. Either they have left the company or have new roles within the company. We have lost a lot of competence." This is supported by another statement:

> "One topic within my area of expertise has been in operations for several years. The person running it retired and we didn't think about transferring that knowledge because 'the process is working'. When we started to get issues, we didn't have anyone that could solve it. The solution was to buy the competence externally."

Several interviewees demonstrate that competitiveness was not a big issue, internal nor external; it seems to be low barriers for them to benchmark and to ask other plants or departments. "We heard another company bought the same machine, so we went to them and had a look." Some lack of trust in others credibility of knowledge is demonstrated. "We used other oils than advised by the supplier and had a lot of problems."

From the interviews the respondents ranked the items below as non-existing or low barriers for knowledge management (the sum of respondents indicating this as a barrier is less than two):

1 Individual:
- fear that sharing may jeopardise people's job security
- use of strong hierarchy or formal power
- difference in experience levels
- lack of contact time and interaction between knowledge sources and recipients
- poor verbal/written communication skills
- age differences
- gender differences
- lack of social network
- differences in education levels
- fear of not receiving fair recognition for intellectual property ownership from managers and colleagues
- lack of trust in people because they may misuse or take unjust credit of the knowledge
- differences in national culture or ethnic background

2 Organisational
- shortage of formal/informal spaces for share, reflect and generate (new) knowledge
- lack of transparent reward and recognition system
- deficiency in company resources that would provide adequate sharing opportunities
- high internal or external competitiveness
- flows of knowledge are restricted to certain directions

- physical work environment restricts effective sharing
- hierarchical organisation structure inhibits sharing practices
- size of business not manageable enough.

3 Technology

- lack of technical support
- unrealistic expectations of employees what technology can or cannot do
- lack of compatibility between IT systems and processes
- mismatch between the needs and requirements of individuals and IT systems and processes
- reluctance to use IT systems
- lack of training in IT systems
- lack of demonstration of advantages of system.

The respondents ranked the items below as barriers for knowledge management (a sum of respondents indicating this as a barrier more than 3):

1 Individual:

- general lack of time to share knowledge
- low awareness and realisation of the value and benefit of possessed knowledge to others
- dominance of sharing explicit over tacit knowledge
- insufficient knowledge capture of past mistakes that would enhance the individual and organisational learning effects
- lack of trust in accuracy and credibility of knowledge.

2 Organisational:

- missing or unclear integration of knowledge reuse into the company's goals and strategy
- lack of practices, leadership and managerial direction that clearly communicates the value of knowledge sharing practices
- existing culture is not providing sufficient support for sharing practices
- knowledge retention of highly skilled and experienced staff is not a high priority
- shortage of appropriate infrastructure supporting sharing practices.

3 Technology

- lack of IT systems and processes impeded the way people do things.

5.3 Supplier collaboration in EEM

In Appendix Table A3, the interviewees' statements are summarised.

All interviewees in all three plants experienced the supplier collaboration as good and close to optimal. One person mentions the positive exchange of knowledge between the company and the supplier. "We know a lot about our equipment that the supplier may now know as they are not running the machines as much as we do." The documentation in one form or another was an issue among all three plants. Five of the interviewees in plant A express that documentation has been, and often is, an issue. As one person describes it: "very often the supplier has another document management system and we want the drawings in our way. We want the machine broken down in sub-systems, electrical system all the way to component level, and then the components divided in spare parts including expected maintenance intervals. Often all this information is there but sorted in a completely different way." One interviewee describes the supplier improving their documentation after receiving feedback. Interviewee five expresses a concern that the case company is getting harder to find suppliers due to their rigorous requirements of documentation. "It is a stack of papers, so I am sure it takes their breath away when they first receive the request for quotation."

Four of the interviewees in the plant B expresses issues with the technical specification (TS) regarding supplier selection of specific components. One example by interviewee I7 is described where it is given in the TS that a specific supplier for control systems should be chosen. From a maintenance perspective, it is beneficial having the same supplier for control systems in all equipment. However, if the equipment supplier has no or little experience of implementing such control system from that specific supplier, it can possibly increase risks. Interviewee I10 even expresses that it sometimes would be beneficial to circumvent TS, because it only hinders the supplier collaboration. The same person also expresses that the possibilities to give input to TS is lacking. All interviewees in plant C describes the supplier collaboration as good or close to optimal. One quote was "the supplier was very workable as far as anything we were looking at. They said it was silly to put this specific feature on, but they were happy to do it and charge us for it." Interviewee I15 explains that the supplier was receptive to design changes. However, it was difficult for the supplier to understand the requirements of the case company's level of documentation, an experience interviewee I18 also shares. Interviewee I13 elaborates on the importance of doing all work upfront in order to reach an agreement of the scope of supply.

6 Analysis and discussion

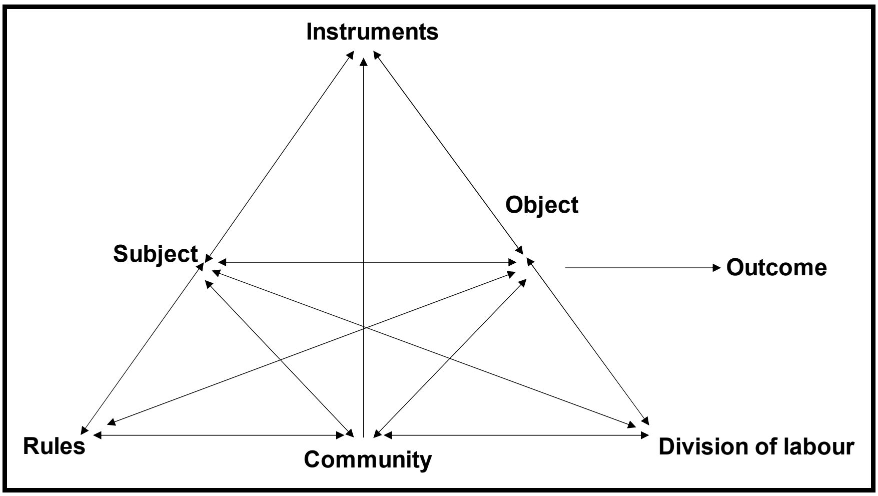
This article is investigating the barriers of how to capture and transfer maintenance related knowledge from operations into the process of procuring new equipment from suppliers. For analysis, other than the knowledge transfer barriers from Riege, the framework of activity theory for organisational learning is used (Engeström, 2000) as described in Figure 3.

For early equipment management, the activity theory model can be described in Figure 4.

As described in the results section, the study identified the following barriers Table 4.

This shows that the main barriers are in the organisational and the individual section but very few in the technology section. The sections below analyse these barriers from an activity theory view.

Figure 3 Activity theory for organisational learning



Source: Engeström (2000)

Figure 4 EEM described in activity theory model

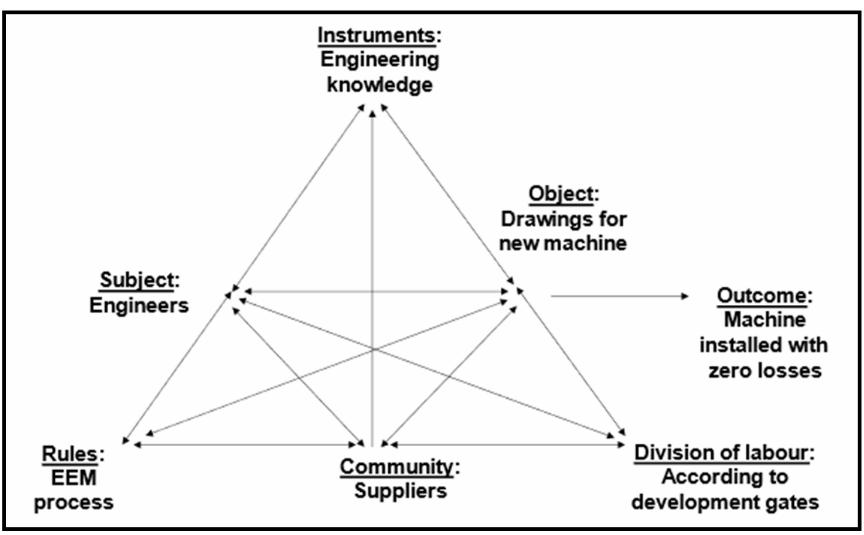


Table 4 Identified knowledge barriers in the study

Individual	*Organisational*	*Technology*
Time	Strategy	IT support
Awareness	Directions	
Explicit vs. tacit	Support	
Capture	Low priority	
Trust	Infrastructure	

6.1 Instruments – engineering knowledge

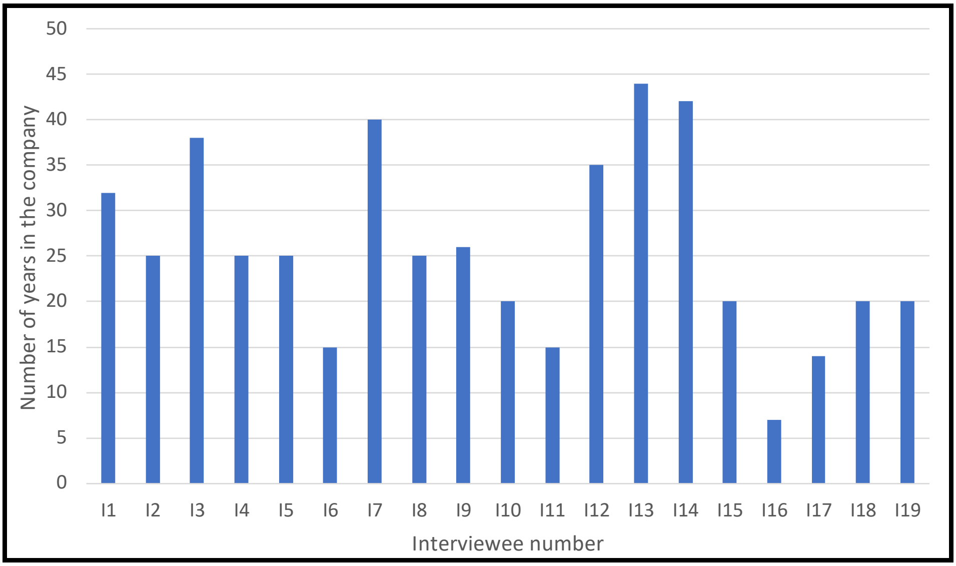
According to the mapping of barriers to knowledge management (Riege, 2005), mapping of the respondents answers shows clearly that some of the barriers are more existing than others and that many suspected barriers were not perceived by the organisation. People did not seem to fear that sharing knowledge would jeopardise anyone's job security; competitiveness (neither internal or external) or organisational hierarchy did seem to be a big issue when it comes to sharing knowledge. Also, any age, gender or cultural differences did not seem to influence knowledge flow in a negative way. Technological barriers were also not seen as big blockers in general.

Barriers that were mentioned as the biggest blockers to effective knowledge management were described from a perspective that knowledge was not seen so important from both an individual and organisational view. For example, there are a few ways of working to collect knowledge, management is not specifically enforcing this activity and there is a lack of infrastructure to either collect share or re-use knowledge. This is a management issue and needs to be addressed as such and refers back to Riege (2005) on organisational barrier number two: Lack of leadership and managerial direction in terms of clearly communicating the benefits and values of knowledge sharing practices. Other barriers were also mentioned that are outside of the Riege (2005) framework. For example, that the level of competence as a total is lowered more and more and that even if the processes exist for documenting knowledge not everyone is applying this way of working. A third thing mentioned is that knowledge is not always documented in an easy way to understand for someone else and that there are difficulties to apply the knowledge from someone in another context.

6.2 Subjects – engineers

As mentioned in the theoretical background, maintenance will play a more and more important role in the circular economy that is growing in the society. Also, from the background research has shown that industry often underestimates the cost of maintenance and the importance of not under investing in maintenance activities. The maintenance competence will therefore be very critical in the future. As can be seen in Figure 5, the respondents have all been in the company or in the role for a significant amount of time. The average number of employment years of the respondents is 26, and the educational level is for almost all high-school or college. The majority started in production as operators and have acquired a detailed and high-level skill in the operations. This background is a very beneficial competence in acquisition projects. All participants were male except one. Perhaps it would be good also with engineers with more experience from outside of the case company and with a higher educational level. Several of the respondents mentioned the good working environment and collaboration willingness that exist in the organisation, especially between sites.

Figure 5 Average age in the company on the role of the respondents (see online version for colours)



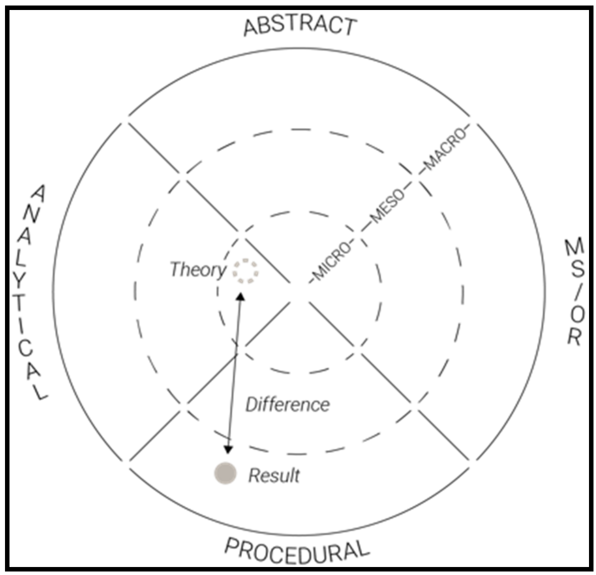
6.3 Rules – the EEM process

When discussing how the interviewees worked with knowledge in EEM, most of the respondents stated that EEM is more a 'what to do and when' checklist, a stage gate model, rather than a knowledge management supporting method. On the topic 'how do you define EEM', 12 respondents defined EEM as a structured way of working; a framework and/or a standardised process (see Appendix Table A1). Regarding the objective of EEM, the answers are more spread depending on the role of the person interviewed but several mentioned classic project objectives such as being on time and on budget. It was evident that the focus from the respondents were more on the phases and gates rather than on the knowledge creation and reuse process to prevent future production disturbances. Referring to theory, this focus from the case company reflects a macro-level procedural model rather than a micro-level analytical model which is where theory suggest knowledge management models are most efficient. This is visualised below in Figure 6.

Traditional stage-gate models (macro-level procedural models) emphasises use of formal, structure reviews to ensure design is sufficiently mature before allowing it to proceed from one stage to the next (Wynn and Clarkson, 2018). Criticism on this approach is that this traditional approach leads to delayed information and reactive management (Ottosson, 2004). He also highlights the difficulty of long-term planning in a project involving uncertainty.

Micro-level analytical models are on the other hand more suitable for knowledge management (Wynn and Clarkson, 2018). One example is the PROSUS method on knowledge modelling (Blessing, 1994). PROSUS focus on as the designer proceeds through iterative cycles, they are intended to capture their knowledge regarding proposals, arguments, and decisions for each encountered design situation. Other models in this section focus on intelligent query of the history to help designers understand and reuse past design, for example the design history system, DHS (Shah et al., 1996).

Figure 6 Visualisation of design models and where knowledge management models are found in the theoretical framework vs. where the model that the case company is using is located in the framework



Source: Wynn and Clarkson (2018)

This finding suggests that the case company might not use the best model to support knowledge management. Also, by looking at the entire EEM system, the knowledge value stream, and not just project by project and compare how much more knowledge is re-used between each acquisition could be valuable. Today the measurements that are used is rather focusing on gates passed on time and vertical ramp-up per project and not on the knowledge re-use part and how much better the entire EEM system is becoming.

6.4 Community – suppliers

Many respondents mention that the collaboration was very good, but six of the interviewees describe difficulties in the supplier collaboration. The difficulties are mainly the structure and the content of the documentation that the case company requires from the supplier. Interviewee 12 even argues that "I definitely would like to share 3D data on product, process and equipment in both directions; I would like them to work directly in our systems with the documentation." Maintenance representative I2 exemplifies a conflict when maintenance needed information and knowledge about a specific component to plan their professional maintenance; "I want to be able to repair this, I cannot just scrap it." The supplier did not want to share their knowledge and information about the specific component since that was their know-how.

It is evident that the information and knowledge sharing through documentation between the supplier and the case company is hindering the collaboration. This seems to affect the quality of the maintenance work in the project; in this case disturbing their work to plan the professional maintenance in an optimal way and by that limiting the possibilities to prevent future production disturbances. Not only does it seem to affect the prevention of future production disturbances, but purchasing representative, I5, even argues that the increasing demand for documentation and maintenance requirements from the case company is making it more difficult to find suppliers that are willing to do business.

Studies has shown that it is critical for any design collaboration initiatives that the requirements are set and agreed (Gullander et al., 2005). Also, the level of supplier responsibility in projects increases the more the design is set by the buyer's requirements (Petersen et al., 2005). This shows that it is necessary for the project success to be detailed and clear on the requirements on both technical aspects but also documentation aspects, even if the interviewees experienced difficulties with the collaboration.

6.5 Division of labour – according to development gates

A large majority of the respondents mentioned this as one of the strong parts of the system that is used, a macro-procedural model with clear stages and gates. The checklists used are specific on which party that should perform a certain task and when, but not necessarily with the depth and the reasoning on why and how to do it, more the what aspect of the task.

All the sites mentioned time and resources as the main challenges. As stated in the theory part, this is normally the case for companies that work with a traditional design process. Shifting towards a more lean approach could be valuable, described in Table 5.

Table 5 Distinction of traditional vs. lean product development

	Traditional	*Lean*
Team structure	Teams not used	Cross-functional teams
Development phases	Small overlap	Simultaneous
Integration vs. coordination	N/A	Meetings
Project management	Functional team structure	Heavy weight manager
Black box engineering	No	Yes
Supplier involvement	Towards the end of the project	From the beginning of the project

Source: Machado and Toledo (2006)

6.6 Objects – technical specifications requirements, spare part lists, maintenance machine ledgers etc.

Twelve of the respondents mentioned the documentation as a concern; both from a content perspective but also as a time-consuming task that required additional resources from both the case company but also the supplier. It was also mentioned as a hinder in collaboration with supplier.

6.7 Outcome – machine installed with zero losses

It was clear that the respondents judged a successful acquisition project depending on their perspective; maintenance were focusing on that it would be easy to maintain the equipment, purchasing focusing on the right cost and production on the capability of the equipment. Only one respondent stated that increased knowledge is one important goal and viewed the benefits from a more holistic view.

7 Conclusions and further work

This paper has presented empiric data from four cases illustrating the need for improved knowledge and information management practices in the purchasing of production machinery. In this paper we have regarded the factory, or specific production equipment in the factory as the system of interest, i.e., the product that is to be improved and delivered. The cases demonstrate clear improvement potential when documenting and transferring knowledge and information about the current product towards the purchasing team of new equipment. Known issues and problems are not satisfactory transferred or requested by the purchasing team. The knowledge of the problems in the existing production machines should influence the buying of the new production machines to ensure the same problems does not occur again. The barriers towards capturing and transferring maintenance related knowledge from operations into the process of procuring new equipment from suppliers has been investigated and analysed from an activity theory perspective. The main conclusions are presented:

7.1 Increase knowledge management awareness for the engineers

In the analysis part, it was identified that the main barriers to effective knowledge transfer between the teams were that knowledge was not seen as important from both an individual and organisational view. This refers to organisational barrier number two: "Lack of leadership and managerial direction in terms of clearly communicating the benefits and values of knowledge sharing practices." This is a management issue and needs to be addressed as such. There needs to be a clear statement from management that it is important to maintain information about the production system over time allowing for knowledge to be reused. Further, streamlined practices, procedures and needed infrastructure needs to be made available to ensure that proper information and knowledge is captured, shared and re-used.

7.2 Enhance the focus to mature tacit knowledge of today to transferable explicit knowledge

It was mentioned by the interviewees that the level of competence as a total is diminished and also that even if the processes exist for documenting information and knowledge not everyone is applying this way of working in a streamlined fashion. Knowledge is not always documented in a way that is comprehension able to the receiver, often lacking information about application and context to make it reusable.

One proposal is to identify ways to share knowledge explicitly, through better documentation practices and training in efficient knowledge transfer procedures. Today tacit knowledge possessed by individuals is transferred by study visits, benchmarking, and training (see Table 3). These activities are normally organised by the teams themselves, which may or may not possess the needed skills to ensure adoption of knowledge at a larger scale. The team members viewed these activities as valuable but there is little effort to ensure that this knowledge is disseminated beyond the immediate team. The proposal of this research study is to increase the emphasis to document explicit knowledge and that efforts are made to ensure organised forums to share tacit knowledge. There are tools and methods that are available and practiced within the organisation that assures reuse of both tacit and explicit knowledge, that can be implemented and evaluated. The aim would be to start a knowledge flow within and between production sites. A similar approach has previously been shown to work in the global engineering organisation (Stenholm, 2018). Stenholm evaluated the specific lean tool 'check sheets' and verified the methodology as a lightweight tool to transfer explicit knowledge over geographical distances as well as over time barriers. The intention of the check sheets is not to manage all existing knowledge and instruct the engineer exactly what to do; instead the aim is to guide the engineer towards making conscious decisions and trade-offs during the design process, in a way that mimics checklists and includes more background information regarding the 'why' and 'how'.

7.3 Increase the diversity in the engineering team set-up

As discussed by Levi (2007), a significant part of creating an effective group is making sure it has the necessary diversity of knowledge and skills. Interdisciplinary research teams are more productive than teams whose members have similar backgrounds. Groups whose members have differences of opinion are more creative than like-minded groups. Management teams whose members have different background and more innovative than homogenous teams (Guzzo and Dickson, 1996). The advantages of diversity are seen when members are both highly skilled and committed to their team's goals. This study showed that the group was to a large extent homogenous and that both productivity and creativity could be increased by including more diversity in the teams in terms of gender, academic background and experience in the company.

7.4 Explore improvements of the design and purchasing model that intensifies lean and learning

The study showed that the company is using a traditional stage-gate model (macro-level procedural models) which emphasise use of formal, structure reviews to ensure that the design is sufficiently mature before allowing it to proceed from one stage to the next (Wynn and Clarkson, 2018). Criticism on this approach is that this traditional approach leads to delayed information and reactive management (Ottosson, 2004). Added to this, is also the difficulty of long-term planning in a project involving uncertainty. Micro-level analytical models are where the design progresses through iterative cycles, intended to capture knowledge regarding proposals, arguments, and decisions for each encountered design situation. One conclusion is that the company should try to emphasise this typical engineering way of working. Also, by looking at the entire EEM system and not just project by project and compare how much knowledge is re-used between each acquisition. Today the measurements that are used is focusing on gates passed on time and vertical ramp-up per project and not at all on the knowledge re-use and the top-level performance of the EEM system.

Typical ways to move forward regarding this principle would be to regard researchers as, e.g., Hoppman (2011). In brief, eleven lean design enablers are relevant to consider for future work within this area:

1. strong project manager
2. specialist career path
3. work-load levelling
4. responsibility-based planning and control
5. cross-project knowledge transfer
6. simultaneous engineering
7. supplier integration
8. variety management
9. rapid prototyping/simulation/testing
10. process standardisation
11. set-based engineering.

7.5 Improve the interface with suppliers

The study shows that there seems to be a trade-off between the level of requirements and ease of collaboration. This means that there is a large potential of improved collaboration could exchange of knowledge and information be managed in a more efficient way. That would disrupt the trade-off and enable a more efficient collaboration with external partners with a higher level of details in the specifications and documentation, resulting in improved equipment. Something that may seem trivial but seems to be a big issue is how to manage the documentation between the case company and the supplier. This creates frustration but could also influence the quality of data that is shared, which could lead to increased cost in terms of unplanned breakdowns etc. To enable this sharing could be a very important step in terms of collaboration.

7.6 Future research

To further explore the potential of PLM and to be able to unlock the productivity gains and increase revenue, there is a need to understand deeper the complexity of knowledge management in industrial system engineering design. More research focus should be put on understanding if we as a society are becoming better at re-using knowledge, perhaps using machine acquisitions as a laboratory for that. It would also be beneficial to analyse the effects of using the stage gate model as the primary model and the impact on the knowledge management quality and suggest ways forward. Also, to understand more and suggest how documentation sharing between partners could be done in a secure but still efficient way, using all the progress that is now taking place under the umbrella of Industry 4.0 technological development.

References

Alavi, M. and Leidner, D.E. (2001) 'Knowledge management and knowledge management systems: Conceptual foundations and research issues', *MIS Quartelry*, pp.107–136.

Bellgran, M. and K. Säfsten (2010) *Production Development - Design and Operation of Production Systems*, Springer-Verlag, London.

Bergsjö, D., Catic, A. and Stenholm, D. (2021) 'A lean framework for reusing knowledge: introducing engineering checksheets', *International Journal of Product Development*, Vol. 25 No. 3, pp.283–302.

Bhasin, S. (2015) *Lean Management Beyond Manufacturing*, Vol. 10, Springer, New York, NY.

Blessing, L.T. (1994) *A Process-Based Approach to Computer-Supported Engineering Design*, University of Twente, Enschede.

Blessing, L.T. and Chakrabarti, A. (2009) *DRM: A Design Research Methodology*, pp.13–42, Springer, London.

Bokrantz, J., et al. (2017) 'Maintenance in digitalised manufacturing: Delphi-based scenarios for 2030', *International Journal for Production Economics* Vol. 191, pp.154–169, https://doi.org/10.1016/j.ijpe.2017.06.010.

Bryman, A.B. (2003) *Business Research Methods*, Oxford University Press, New York.

Denscombe, M. (2014) *The Good Research Guide: for Small-Scale Social Research Projects*, McGraw-Hill Education (UK).

Engeström, Y. (2000) 'Activity theory as a framework for analysing and redesigning work', *Ergonomics*, Vol. 43, No. 8, pp.960–974.

Grieves, M. (2006) *Product Lifecycle Management - Driving the Next Generation of Lean Thinking*, McGraw-Hill companies, New York, NY.

Gulati, R. (2013) *Maintenance and Reliability Best Practices*, 2nd ed., Industrial Press, New York, NY.

Gullander, P., et al. (2005) *Effektivare Tillverkning! Handbok För Att Systematiskt Arbeta Bort Produktionsstörningar*, IVF Uppdragsrapport 05/22, Stockholm, Swedish Institute for Standards.

Guzzo, R.A. and Dickson, M.W. (1996) 'Teams in organizations: recent research on performance and effectiveness', *Annu. Rev. Psychol.*, Vol. 47, No. 3, pp.307–38.

Hane Hagström, M., et al. (2020) 'Evaluating the effectiveness of machine acquisitions and design by the impact on maintenance cost – a case study', *IFAC-PapersOnLine*, Vol. 53, No. 3, pp.25–30.

Hoegl, M. and Wagner, S. (2005) 'Buyer-supplier collaboration in product development projects', *Journal of Management*, Vol. 31, pp.530–548.

Hoppman, J.E., et al. (2011) 'A framework for organising lean product development', *Engineering Management Journal*, Vol. 23, No. 1, pp.3–15.

J.R.X., A. and Alves, J.M. (2015) 'Production management model integrating the principles of lean manufacturing and sustainability supported by the cultural transformation of a company', *International Journal of Production Research*, Vol. 53, No. 17, pp.5320–5333.

Jha, K. and Iyer, K. (2007) 'Commitment, coordination, competence and the iron triangle', *International Journal of Project Management*, Vol. 25, No. 5, pp.527-540.

Kennedy, M. (2008) *Ready, set. Dominate: Implement Toyota's Set-Based Learning for Developing Products and Nobody Can Catch You*, Oakley Press, Richmond, VA.

Lasi, H., et al. (2014) 'Industry 4.0', *Business & Information Systems Engineering*, Vol. 6, No. 4, pp.239–242.

Lehner, F. and Maier, R.K. (2000) 'How can organisational memory theories contribute to organisational memory systems?', *Information System Frontiers*, Vol. 2, No. 3, pp.277–298.

Levi, D. (2007) *Group Dynamics for Teams*, p.24, SAGE.

Lundgren, C. (2019) *Smart Maintenance Investments*, PhD thesis, Chalmers University of Technology.

Machado, M. and Toledo, N. (2006) 'Criacao de valor no processo de desenvolvimento de produto: uma avalicao da aplicabilidade dos principios e praticas enxutas', *Revista Gestao Industrial*, Vol. 2, No. 3, pp.142-153.

Mathison, S. (1988) 'Why triangulate?', *Educational Researched*, Vol. 17, No. 2, pp.13–17.

Morgan, J. and Liker, J. (2006) *The Toyota Product Development System: Integrating People, Process and Technology*, Productivity Press, New York, NY.

Natarajan, S., et al. (2019) 'How do knowledge domains come together in systems? Cham, Switzerland, Systems Engineering in context, Springer, *16ths Annual Conference on Systems Engineering Research*.

Ottosson, S. (2004) 'Dynamic product development – DPD', *Technovation*, Vol. 24, No. 3, pp.207–217.

Petersen, K., et al. (2005) 'Supplier integration into new product development: coordinating product, process and supply chain design', *Journal of Operations Management*, Vol. 23, pp.371–388.

Riege, A. (2005) 'Three-dozen knowledge-sharing barriers managers must consider', *Journal of Knowledge Management*, Vol. 9, No. 3, pp. 18–35.

Salonen, A. (2018) 'The need for a holistic view on dependable production systems', *Procedia Manufacturing*, Vol. 25, No. 8, pp.17–22.

Salonen, A. and Tabikh, M. (2016) 'Downtime costing - attitudes in Swedish manufacturing industry', *Proceedings of the 10th World Congress on Engineering Asset Management (WCEAM 2015)*, pp.539–44.

Shah, J., et al. (1996) 'Database infrastructure for supporting engineering design histories', *Comput Aided Des*, Vol. 28, No. 5, pp.347–360.

SIS (2000) *SS 441 0505, Dependability – Terminology*, Swedish Institute for Standards, Stockholm.

Stenholm, D. (2018) '*Reuse of Engineering Knowledge: Support for Effective Reuse of Experience-Based Codified Knowledge in Incremental Product Development*, PhD thesis, Chalmers University of Technology.

Stenholm, D. (2018) *A Lean Framework for Reusing Knowledge - Introducing Engineering Check Sheets*, Gothenburg, Chalmers.

Tortorella, G.L. et al., (2016) 'Relations between lean product development enablers and problems', *International Journal of Production Research*, Vol. 54, No. 10, pp.2837–2855.

Tryon Jr, C.A. (2016) '*Managing Organisational Knowledge: 3rd Generation Knowledge Management and Beyond*, CRC Press, Boca Raton, Florida.

Wakiru, J. et al. (2018) 'Maintenance optimization: application of remanufacturing and repair strategies', *Copenhagen, 25th CIRP Life Cycle Engineering Conference*, 30 April–2 May.

Ward, A. (2007) *Lean Product and Process Development*, Lean Institute, Boston, Massachusetts.

Webster, J. and Watson, R.T. (2002) 'Analyzing the past to prepare for the future: Writing a literature review', *MIS Quartelry,* Vol. 26, No. 2, pp.13–23.

Weyer, S., et al. (2015) 'Towards Industry 4.0 - standardisation as the crucial challenge for highly modular, multi-vendor production systems', *Ifac-Papersonline*, Vol. 48, No. 3, pp.579–584.

Womack, J.P., et al. (1990) *The Machine That Changed The World*, Maxwell, MacMillan International, New York.

Wynn, D. and Clarkson, P. (2018) 'Process models in design and development', *Research in Engineering Design*. Vol. 29, pp.161–202, DOI: 10.1007/s00163-017-0262-7.

Yeo, K.T. and Ningm, J. (2006) 'Managing uncertainty in major equipment procurement in engineering projects', *European Journal of Operational Research*, Vol. 171, No. 1, pp.123–134.

Appendix

Interview guide

1 Your general role

a Tell me about your career up until today

b Tell me about your position today

c How does a typical work week look for you?

2 Early equipment management

a What does EEM mean to you?

b Could you describe the objective with an EEM project?

- How do you know if the project was a success?

c What are the biggest challenges in EEM?

d Could you describe the project from your perspective?

e Could you describe your role in the project?

f How did the project make sure that previous losses were not transferred into the new equipment?

g Do you know how the equipment is performing today?

3 Supplier collaboration

a How would you describe the collaboration between the project and the supplier?

- How did the project collaborate with the supplier regarding maintenance?
- What information would you like to share with the supplier?

b Could you describe the optimal supplier collaboration?

c What do you see as the biggest challenges to reach that collaboration?

4 Knowledge management

a Could you give an example of when you faced a problem in the project that could have been avoided had you had more information?

- How did you solve that problem?
- Would it have been possible to avoid?

b You have a lot of experience; do you think it would be possible for someone new to the work to do your task solely depending on the documented processes?

- Does ‘design review ‘ring a bell for you? It is a checklist that tries to make sure that nothing important is forgotten. What do you think about that idea?
- ‘Project office’ is a concept that in theory means that an organisation has a function that has the main purpose of capturing knowledge from completed projects and channel to new projects. What do you think about that?
- How do you use ‘white books’?
- How is the success of projects measured?

Table A1 Summary of interviews regarding the definition of EEM focusing on the maintenance persperceive

Plant	*Inter-viewed*	*Role*	*Statements*
A	1	Project leader	In general, EEM is a good, structured way of working in order to know what, when and how to work
A	2	Mechanical maintenance	Knowing exactly what is needed to do as early as possible by including lessons learned from previous equipment
A	3	Mechanical maintenance	EEM is about documents, gates, and being able to choose an equipment that meets the criteria
A	4	Electric maintenance	EEM is procurement of equipment
A	5	Purchasing	EEM is a method in which you work in groups and use methods and tools to minimise risks in procurement and learn from previous experiences
A	6	Operator	EEM is about knowing exactly what is needed to do as early as possible by including lessons learned from previous equipment
B	7	Process owner	A framework for how they should work when procuring equipment before, during and after
B	8	Process owner	EEM is an effort to work in a structured way with procurement
B	9	Maintenance manager	EEM is a standardised procurement process in order to set requirements for the supplier
B	10	Mechanical maintenance	EEM is about making improvements in new equipment through white books
B	11	Electric maintenance	EEM is a structure with a list of points to work with
B	12	Purchasing	EEM is an effort to work in a structured way with investments
C	14	Project leader	EEM is a systematic process for procuring equipment, making sure all requirements are covered
C	15	Maintenance manager	EEM is about longevity. The meaning of the philosophy is to find out how to maintain the machine with the highest possible up-time and minimise the downtime
C	16	Mechanical maintenance	EEM is a process that allows us them to give input to the project
C	17	Electric maintenance	EEM means setting up a workable professional maintenance complaint with what they are used to before the machine is installed
C	18	Purchasing	EEM is a structure that support their function during the procurement process
C	19	Operator	Involving operators during the procurement process to get the sufficient training to run the equipment
A	1	Project leader	The goal is to get better equipment, not only a replacement
A	2	Mechanical maintenance	The goal is to buy equipment that us reliable and available, production organisation should be satisfied
A	3	Mechanical maintenance	The goal is to get a better machine with 98% availability
A	4	Electric maintenance	The goal is to be able to deliver and make the customer satisfied
A	5	Purchasing	The goal is to minimise the risk and buy the optimal equipment, in terms of cost over time
A	6	Operator	The goal is to get equipment that is reliable and available, production should be satisfied
B	7	Process owner	To invest in an equipment that we will use in our production
B	8	Process owner	To get a process that is as disturbance free as possible

Table A1 Summary of interviews regarding the definition of EEM focusing on the maintenance persperceive (continued)

Plant	*Inter-viewed*	*Role*	*Statements*
B	9	Maintenance manager	To know what to do and when to do it
B	10	Mechanical maintenance	To get equipment without early defects, with recommendable spare parts and maintenance lists
B	11	Electric maintenance	That the equipment should be able to produce and deliver results but also be maintainable
B	12	Purchasing	To get equipment that live up to expectations and demands on time to the right price, also to minimise risks
C	13	Project leader	To get everybody's requirements
C	14	Project leader	To purchase an equipment that meets all requirements
C	15	Maintenance manager	To make sure that the equipment is easily maintained to achieve highest possible up-time and minimised down-time
C	16	Mechanical maintenance	To have a better machine coming into the building
C	17	Electric maintenance	More up-time and less down-time
C	18	Purchasing	Making sure that the purchasing organisation is involved during each step rather than when it is too late
C	19	Operator	Avoiding prior experience of less successful projects by involving production and maintenance
A	1	Project leader	To only buy one piece of equipment when part of the process is created to build entire lines
A	2	Mechanical maintenance	Limited amount of time
A	3	Mechanical maintenance	To install equipment into a producing line
A	4	Electric maintenance	To get a good overview of large projects
A	5	Purchasing	Limited amount of time and knowing what competence you need
A	6	Operator	Limited amount of time
B	7	Process owner	The internal customer needs to know what they want in order to set the right requirements
B	8	Process owner	Limited amount of time, usually a result in the usage of shortcuts and cope-paste solutions
B	9	Maintenance manager	Lack of competence
B	10	Mechanical maintenance	Limited amount of time and too many projects at the same time
B	11	Electric maintenance	The challenge is to get (acceptance) of input from maintenance into the project. The balance between the operators' and the maintenance workers' environment
B	12	Purchasing	Limited number of resources and an internal resistance (to buy) for standard equipment
C	13	Project leader	The biggest challenge is that it is labour intense, so it becomes very busy
C	14	Project leader	The balance between using suppliers and processes that are known to the company and getting the best fit for the plant
C	15	Maintenance manager	To get people to understand the philosophy
C	16	Mechanical maintenance	Being new to the process, knowing what to keep an eye on
C	17	Electric maintenance	Cooperation is the biggest challenge
C	18	Purchasing	Getting suppliers to agree on the high workload
C	19	Operator	Making sure that the operators get involved and trained to run the production after installation

Table A2 Summary of interviews regarding knowledge management in EEM project, focusing on the maintenance perspective

Plant	*Inter-viewed*	*Role*	*Comments*
A	1	Project leader	Uses IPAP as a to-do list to remember what and when to do important activities. I have never updated the list.
A	2	Mechanical maintenance	Contacts different people, e.g., operators and maintenance in order to collect knowledge and experience during the project
A	3	Mechanical maintenance	Uses MPAP as a to-do list for knowing what activities to do and when they should be performed, has performed interviews with maintenance personnel, technicians and operators to get their knowledge and experience of the current equipment
A	4	Electric maintenance	Contacts the maintenance organisation and extracts data from all emergency breakdowns in the maintenance system. These are then analysed and concentrated into a list of improvements for the supplier. The person tries to involve an influential operator to gain buy-in.
A	5	Purchasing	Shares a lot of information and knowledge with the supplier, specifically if there has been reoccurring procurements. However, feels that the case company does not share enough information during operations to the supplier, which will be a challenge in Industry 4.0.
A	6	Operator	Took own initiative to collect a list of potential improvements among the operators. Did a study visit to an outside company to benchmark and get ideas for improvements?
B	7	Process owner	White books are often never written, they keep them in their hear. They are cautious of sharing all knowledge since they see themselves as knowledge leaders in the industry.
B	8	Process owner	White books are primarily to develop from previous projects. The level of knowledge is low and it is difficult to find appropriate knowledge.
B	9	Maintenance manager	White books are used primarily to develop from previous projects. It is difficult to capture and develop knowledge since the projects occur so seldom and there is a high degree of employee turn-over. There has been a lack of knowledge in several previous projects. All knowledge is implicit.
B	10	Mechanical maintenance	The level of knowledge is low. There is no possibility to capture new ideas for improvements info future projects. Previously there has been a process of incorporating breakdown knowledge into the projects, but not anymore.
B	11	Electric maintenance	The level of knowledge in EEM has decreased the last 15 years. There is a lack of possibility to capture new ideas for improvements into future projects.
B	12	Purchasing	The technical specification is a form of white book used to eliminate the risk of repeating the same mistake twice
C	13	Project leader	If you follow the formal process, it will make you avoid missing any knowledge needed in the project
C	14	Project leader	Reviewing break down data, study visits in Plant B with the entire team and weekly meetings with experienced team members in Plant B is the main way to share and secure knowledge
C	15	Maintenance manager	There is a large variation on lessons learned depending on who writes them. Break down data and human error analysis are the most important knowledge for the project.
C	16	Mechanical maintenance	Study visits at Plant B with the entire team. The person is not aware of any way to give feedback for future equipment.
C	17	Electric maintenance	Has experience of projects where knowledge about needs is not shared to the supplier. New ideas for improvements are shared through meetings. Weekly meetings to integrate maintenance has proven successful.
C	18	Purchasing	Hopefully the technical group learns from past mistakes and re-writes the specification to reflect that.
C	19	Operator	The person worked together with operators at Plant A to gain and share knowledge. Trainings from the supplier have improved.

Table A3 Summary of interviews regarding supplier collaboration in EEM projects, focusing on the maintenance perspective

Plant	*Inter-viewed*	*Role*	*Comments*
A	1	Project leader	Good experience, documentation is often an issue
A	2	Mechanical maintenance	Good experience, improved documentation after feedback
A	3	Mechanical maintenance	Good experience, documentation is often an issue
A	4	Electric maintenance	Good collaboration. Inputs were noticed by the supplier
A	5	Purchasing	Good experience, it is becoming harder to find suppliers due to the company's requirements on documentation
A	6	Operator	Good experience, it is beneficial to use the same supplier as in previous projects
B	7	Process owner	Good experience, there is a trade-off between the supplier's choice of components and the technical specification from us
B	8	Process owner	Good experience from several projects. There is a risk when sharing information, also a trade-off between supplier's choice of components and our technical specification
B	9	Maintenance manager	Good experience, there is a trade-off between the supplier's choice of components and the technical specification from us
B	10	Mechanical maintenance	There is no possibility to give input to the technical specification. There is a trade-off between the supplier's choice of components and the technical specification from us
B	11	Electric maintenance	Good experience, it would be optimal to select the supplier as early as possible.
B	12	Purchasing	Need to support supplier with documentation. Single sourcing vs. multiple sourcing give trade-offs.
C	13	Project leader	Close to optimal collaboration, it is critical to agree in the scope of supply.
C	14	Project leader	Issue of selecting supplier, both in communication and format of quoting.
C	15	Maintenance manager	The supplier is receptive for design inputs, but it is difficult for them to understand our requirements for documentation.
C	16	Mechanical maintenance	Close to optimal collaboration, the supplier is very supportive
C	17	Electric maintenance	Close to optimal collaboration except for a few issues
C	18	Purchasing	It is difficult for suppliers to understand our requirements on documentation
C	19	Operator	Good experience and support in training