Manufacturing Technology Readiness Assessment

Mats Ahlskog (mats.ahlskog@mdh.se)
Department of Product Realisation, Mälardalen University, Sweden

Mats Jackson
Department of Product Realisation, Mälardalen University, Sweden

Jessica Bruch
Department of Product Realisation, Mälardalen University, Sweden

Abstract
The purpose of this paper is to analyze and discuss how the MRL scale can support the assessment of a manufacturing technology's maturity level. A single case study within the manufacturing industry has been conducted investigating the use of a MRL scale. An assessment of MRL 4 has been studied.

Keywords: Maturity level; Manufacturing Readiness Level; Manufacturing industries

Introduction

To stay competitive on a global market, manufacturing companies need to focus on the development of new products. Still, this is very much related also to the development of the manufacturing system. An effective product introduction into the manufacturing system have a major impact on the success of product development projects and thus companies competitiveness (Bellgran and Säfsten, 2010; Hayes et al., 2005). In the early phases of the product development, innovative product functions and solutions are often being developed by R&D. A commonly used scale to determine the maturity level of products being developed is the technology readiness level (TRL) developed by NASA (Mankins, 2009b; Mankins, 2009a; Fernandez, 2010; Sauser et al., 2006). The TRL scale helps product development projects to stay within time and budget. In this article, "technology readiness" and "technology maturity" are treated as synonyms in line with previous studies (Azizian et al., 2011; Tetlay and John, 2009). However, if early R&D of products is implemented poorly, product development projects will suffer from cost overruns, schedule delays and steady erosion of initial performance objectives (Mankins, 2009a; Cooper, 2011).

The trend within the manufacturing industry has been to decrease product development time in new product development (NPD) projects and thereby have a faster time-to-market (Cooper, 2011; Trott, 2012). But, development of new products frequently drives the need of investments in manufacturing technology (Bruch, 2012; Rönnberg Sjödin, 2013) which increases the complexity of the product development projects as an external equipment supplier need to become integrated (Ragatz et al., 1997; Abd Rahman et al., 2009). Modern manufacturing technology plays also a key role in the ability of manufacturing enterprises to compete as world class manufacturers. Investment in new manufacturing technologies enables manufacturing companies to hold and increase their competitive advantages (Reinhart and Schindler, 2010). Managers need to make complex decisions regarding applicable technologies in order to gain optimal return on manufacturing technological investment (Pretorius and de Wet, 2000). Previous studies show that in order to become competitive on a global market managing of manufacturing technology is a vital issue (Phaal et al., 2001; Monge et al., 2006).

Despite the potential benefits many manufacturing companies are still struggling with evaluation and introduction of new manufacturing technology during NPD (Gupta et al., 1997; Costa and Lima, 2009). Manufacturing companies have to evaluate potentially useable manufacturing technologies with regard to their capabilities and core-competencies in order to stay competitive. Implementing new manufacturing technologies into an existing production environment is time-consuming and can be connected to risks if un-mature technologies are being used. Therefore, the decision in favor or against an alternative is a very crucial and strategic decision.

In order to handle this challenge, manufacturing companies need an applicable model to support the decision process of choosing the most appropriate manufacturing technologies (Greitemann et al., 2014). One way to assess maturity level of manufacturing technologies is with the manufacturing readiness level (MRL) framework. The MRL scale can serve as a helpful knowledge-based standard and shorthand for evaluating manufacturing maturity, but they must be supplemented with expert professional judgment of MRL (DoD, 2012).

In previous research studies the main focus has been on TRLs and although MRLs have been proposed for improving the way of assessing manufacturing risks and readiness it has not been used as broadly as TRLs (Fernandez, 2010). Further, Frishammar et al. (2012) mean that, more research is needed in the early phases of manufacturing technology development projects, because prior research has concentrated on product development.

Therefore, the purpose of this paper is to analyze and discuss the assessment of a manufacturing technology's maturity level. A single case study within the manufacturing industry has been conducted investigating the practical use of a MRL scale. An assessment of MRL 4 (capability to produce the technology in a laboratory environment) has been studied and the framework used in the assessment originates from U.S. Department of Defense (DoD, 2012). The results that will be discussed concerns the challenges and risks in the actual assessment of the assembly system.

The paper is outlined as follows. In the next section the theoretical framework is presented. The following two sections encompass the research design, followed by the findings. Finally, the paper concludes by discussing challenges and risks, as well as suggestion for further research within this area.

Theoretical Framework

Technology Readiness Level (TRL)

Since, Mankins (1995) for the first time described the TRL scale used by NASA in his white paper, "Technology readiness levels", the TRL scale has been adopted and further developed by other agencies and industries (Mankins, 2002; Homeland Security, 2009; Mankins, 2009b; Sauser et al., 2006; Tan et al., 2011). Originally the idea with the TRL scale was to articulating the status of a new technology planned for use in a future space system (Mankins, 2009b). The TRL scale can be considered as a systematic metric/measurement system that supports assessments of the maturity of a particular technology and the consistent comparison of maturity between different types of technology (Mankins, 1995; Sauser et al., 2006). Further, the TRL scale is commonly used in R&D and product development projects to improve the outcome and maintaining cost and schedule within a project. A higher level of maturity means that the technology is more mature in its development life cycle (Homeland Security, 2009; Mankins, 2009a).

To determine the readiness level of a technology, assessment should be conducted at several points during the development life cycle of a new technology (Mankins, 2009b). These Technology Readiness Assessments (TRAs) are the points when an organization attempts to determine the maturity of a new technology and/or capability (including required levels of engineering or economics-related performance). Kujawski (2013) state that there are several different assessment methods for TRLs, and these TRLs are often used interchangeably in the literature and simply referred to as “TRL”.

Manufacturing Readiness Level (MRL)

The U.S. Department of Defense (DoD) introduced the concept of Manufacturing Readiness Levels (MRL) to expand TRL to incorporate producability concerns related to risks associated with time and manufacturing (Islam, 2010; Sauser et al., 2006). Further, the MRL scale builds on best practice for conducting assessments of manufacturing readiness (DoD, 2012). MRLs and assessments of manufacturing readiness have been designed to manage manufacturing risks in acquisition projects while increasing the ability of the technology development projects. Since the first MRL scale was developed by DoD, different MRL scales have been developed by other agencies and organisations e.g. Automotive Council UK (2011) and Joint Defense (2007). Automotive Council UK (2011) describes the relationship between TRL and MRL as; deliver its function (technology readiness) and being produced (manufacturing readiness).

In order to have an effective and efficient manufacturing system development it demands to work with R&D within manufacturing and use some sort of MRL scale to assess new evolving manufacturing technologies (Bruch and Bellgran, 2013; Bellgran and Säfsten, 2010). New manufacturing technologies or processes need to be evaluated throughout their development cycle. To determine the maturity level of new manufacturing technologies, decisions needs to be taken regarding if they can be acquired and implemented into the manufacturing system.

The MRL scale developed by U.S. Department of Defense consists of ten readiness levels which directly relate to the nine TRLs (see, Figure 1). Manufacturing readiness and technology readiness go hand-in-hand. MRLs, in conjunction with TRLs, are key measures that define risk when a manufacturing technology or process is matured and can be transferred to a manufacturing system. Manufacturing processes will not be able to mature until the product technology and product design is stable. MRLs can also be used to define manufacturing readiness and risk at the system or subsystem level. According to DoD (2012), the MRL definitions were designed to include a nominal level of technology readiness as a prerequisite for each level of manufacturing readiness. Also, to provide decision makers (at all levels) with a common understanding of the relative maturity (and attendant risks) associated with manufacturing technologies, products, and processes being considered to meet requirements (Joint Defense, 2007; DoD, 2012).

MRL Definitions

Full-Rate Production	MRL 10	TRL 9	**Full Rate Production demonstrated and lean production practices in place** System, components or items are in full rate production and meet all engineering, performance, quality and reliability requirements
FRP			
Low-Rate Initial production	MRL 9	TRL 9	**Low rate production demonstrated; Capability in place to begin Full Rate Production** Full rate production and minimal system changes
C			
Engineering & Mfg Development	MRL 8	TRL 8	**Pilot line capability demonstrated; Ready to begin Low Rate Initial Production** Manufacturing and quality processes and procedures have been proven in a pilot line environment and are under control and are ready for low rate production.
Engineering & Mfg Development	MRL 7	TRL 7	**Capability to produce systems, subsystems, or components in a production representative environment** Manufacturing processes and procedures have been demonstrated in a production environment
B			
Technology Development	MRL 6	TRL 6	**Capability to produce a prototype system or subsystem in a production relevant environment** Prototype manufacturing processes and technologies, materials, tooling and test equipment, as well as personnel skills have been demonstrated on system and/or subsystem in a production relevant environment
Technology Development	MRL 5	TRL 5	**Capability to produce prototype components in a production relevant environment** Produce prototypes in a production relevant environment, but many manufacturing processes are still under development
A			
Material Solution Analysis	MRL 4	TRL 4	**Capability to produce the technology in a laboratory environment** Processes to ensure manufacturability, producibility, and quality are in place and are sufficient to produce technology demonstrators.
Pre Material Solution Analysis	MRL 3	TRL 3	**Manufacturing Proof of Concept Developed** Validation of the manufacturing concepts through analytical or laboratory experiments.
Pre Material Solution Analysis	MRL 2	TRL 2	**Manufacturing Concepts Identified** Describing the application of new manufacturing concepts.
Pre Material Solution Analysis	MRL 1	TRL 1	**Basic Manufacturing Implications Identified** Basic research (i.e. found by budget activity) begins in the form of studies.

Figure 1 - Summary of MRL definitions for each readiness level. Adopted from DoD (2012).

Further, there are two types of decision points in the MRL scale: milestone decisions and decision reviews. Milestone decision points initiate projects and authorize entry into the major acquisition process phases and decision reviews assess progress and authorize (or halt) further project activity (Joint Defense, 2007). Cooper (2011) argues that one of the greatest failures in development projects is senior management issues, namely, overloading the development pipeline. Far too many projects are approved at decision points before considering the resources available. However, at each decision point a decision is taken to initiate, continue, advance, or terminate a project or program. The review associated with each decision point typically addresses program progress and risk, affordability, program trade-offs, acquisition strategy updates, and the development of exit criteria for the next phase or effort. Joint Defense (2007) mean that the number of decision points should be tailored to program needs. There are three major milestone decision points that initiate programs and authorize entry into the major acquisition process phases (see, Figure 1): Milestone A: Technology Development (TD), Milestone B: Engineering and Manufacturing Development (EMD) and Milestone C: Low Rate Initial production (LRIP) (DoD, 2012).

Manufacturing Readiness Assessment (MRA)

DoD (2012) describes an assessment of manufacturing readiness as a structured evaluation of a technology, component, manufacturing process or subsystem. It is performed to: define current level of manufacturing maturity, identify maturity shortfalls and associated costs and risks, and provide the basis for manufacturing maturation and risk management (DoD, 2012). In the literature, various explanations and definitions of assessment and evaluation can be found. Säfsten (2002) claim that evaluation deals with three main questions; knowledge, judging, and use of result. Further, Derelöv (2009) argues that evaluation is the activity which, in most cases, precedes a decision. The objective with an evaluation is to collect and compare information from the different alternatives. Homeland Security (2009) describes an assessment as; the evaluation and interpretation of measurements and other information to provide a basis for decision making. Moreover, Bellgran and Säfsten (2010) highlights that evaluation constitutes an important part of the work in manufacturing system development. Studies carried out among manufacturing companies shows that evaluation is often a neglected activity. Evaluation is often considered as important, but only a few take time to carry out an evaluation. Lack of time is often given as the reason for not evaluating; not knowing to do it is another reason, or a combination of both (Bellgran and Säfsten, 2010).

Further, DoD (2012) mean that there should be a well-defined hierarchy among the elements being assessed, when an assessment of manufacturing readiness is performed. The hierarchy should start at a high level and flow down to the lowest component that forms the smallest unit for examination (DoD, 2012). Moreover, the assessment should be performed by teams consisting of subject matter experts that are experienced and knowledgeable in the assessed areas to identify potential manufacturing constraints, risks, and the capability of the manufacturing technology (DoD, 2012; Bellgran and Säfsten, 2010). Finally, the assessment team should include the actions necessary to bring readiness up to the target level in time to transition a manufacturing technology or support a milestone decision with manageable risk.

Tan et al. (2011) summarizes the most common approaches to performing readiness level assessments, as:

1. Individual estimation: A subject matter expert assesses the maturity of a technology.
2. Group discussion estimation: holding a meeting or conference to discuss the technology maturity.
3. Individual-group estimation: Subject matter experts first perform independent estimations and then discuss these independent estimates in a collective manner to arrive at a consensus of a single estimate.

Challenges and limitations

In the literature different challenges, risks, and limitations can be found regarding MRL and MRL/TRL relationship. Homeland Security (2009) mean that a limitation of the MRLs is that the lower MRL levels can be difficult to correlate to corresponding TRL numbers due to the technology immaturity (i.e., it is difficult to know what types of manufacturing steps are required when a technology concept has not yet been proven). Further, Mankins (2009b) mean that there are a range of challenges, both organizational and methodological facing the technology assessment community. For example, achieving the right level of technology maturity across multiple subsystems and components is an on-going challenge to development success of all advanced technology systems. Moreover, Tan et al. (2011) argue that ambiguous words used in the readiness level definitions, such as “relevant environment”, can lead to various interpretations in different applications. Also, the data and additional qualitative information which are usually provided by the engineering managers forming the basis of an assessment may not be thorough or in the matching format for performing an assessment. Furthermore, Mankins (2009b) points out that the key data necessary to conduct an effective TRA, should contain; 1. A clear understanding of the performance objectives for the new technology and/or system capability. 2. The current TRL for the technology and/or system capability in question, as well as for any key supporting technologies. 3. To develop a clear understanding of the remaining "development hurdles" and the projected uncertainty in the likelihood of development success for novel technologies. Joint Defense (2007) state that effective technology transition requires an effective and continuing dialogue between technology managers, technology developers and technology customers. DoD (2012) mean that MRLs can serve as a helpful knowledge-based standard and shorthand for evaluating manufacturing maturity, but they must be supplemented with expert professional judgment.

Research Design

This study has been conducted in two parts, a literature review regarding MRL and TRL concepts, and a single case study within the manufacturing industry. The literature review aimed also to find out the relationship between the MRL and TRL scale, and how these concepts have been developed over time, as well as their challenges and limitations. However, main focus has been on the MRL scale developed by U.S. Department of Defense, and the MRL scale was also used by the case company in this study.

A case study method has been chosen in order to analyze challenges and risks in the assessment of an assembly systems maturity level. Applying a case study method provides the opportunity to use different techniques for data collection and multiple source of data (Yin, 2009) supporting the ability to gather a rich set of data from observation, interviews, documents and to study the phenomenon that is not all understood (Voss et al., 2002; Yin, 2009).

The case study has been conducted at a manufacturing company and the plant where the study has been conducted is characterized by a high level of automation and final assembly of products is made in the plant. Further, in a production development project the case company tried to combine four different product platforms so that they could be assembled in one assembly system. The maturity level of this assembly system where assessed by two external auditors from other functions within the company and a modified MRL scale from U.S. Department of Defense was used for assess MRL 4. The main idea behind this assessment in this case was to apply the TRL concept in a manufacturing context.

Data was collected through the ongoing assembly system development project through participation in the development project, document analysis, and at two formal one hour meetings during the MRL 4 assessment of the assembly system by external assessors:

- **Meeting 1**: At the start-up meeting the production development project and associated project documentation was presented for the auditors, as well as the areas in the MRL 4 framework that would be assessed.

- **Meeting 2**: One week later, a follow-up meeting was held with the auditors where the comments were reviewed and documented as an input to a coming (MRL4) gate presentation to the steering committee for the project.

Empirical Findings

The case study company is a global manufacturer with multiple manufacturing sites. The project reviewed in the case study has been focusing on the design of a large-scale mixed-product assembly concept. The assembly project has been attempting to find solutions to mix assembly of very different products from different manufacturing sites in the same main assembly flow (assembly line). This includes overcoming challenges to handle different product design, length and weight in the same assembly flow. The project is global with representatives/representative factories from different sites around the world, e.g. Korea, USA, Germany, Poland, and Sweden with competence about their products, assembly processes and methods. The project was divided into four development areas (1) the development of a main assembly line concept, (2) the development of a material handling/logistics solution connected to assembly and the proposed assembly concept, (3) investigations of a possible application and implementation of the concept in a specific factory, and (4) the specification of flexible requirements on product development.

A first analysis of current products within the corporation resulted in a first proposal for grouping of products. For this, aspects such as: size – weight and product design, assembly process, sequence and tooling, volumes and assembly times were considered. This grouping exercise was used in selecting a first group of products to start the detailed assembly system development. The detailed development of the main line concept continued towards a layout/process proposal with the main principles of;

- having a generic assembly sequence,
- using generic assembly zones – a clear zone/station for defined major product modules,
- using standardized and common interfaces towards sub-assemblies/product modules,
- common tooling/equipment in each zone.

Based on this a first generated line concept and layout was generated. More data was collected regarding e.g. detailed work content for each product in each zone. Specific analysis has also been done regarding necessary tooling and equipment.

In order to increase the maturity of the concept a prototyping of the concept was done during the fall of 2014. Different products have been assembled together to test manufacturing technology challenges in e.g. tooling and equipment. The objective of the prototyping was also to identify product design characteristics, necessary to be changed in order to make the assembly concept feasible and competitive. The goal with the prototyping was to reach MRL 4.

To determine the maturity level of the assembly system a MRL framework was used which was based on the developed framework by U.S. Department of Defense. The MRL framework and assessment was used for the first time at the case company and provided a case for further manufacturing system development and process development. Further, the two external auditors came from two different functions within the company (see, Table 1) and are experienced within pre-development of products and technology readiness assessment for products.

Table 1 - The auditor's work task

Auditor	**Work task**	**Function**
A	Pre-development of products	Technology Project office
B	Pre-development of products	AE Project office

The normal procedure at the company performing a technology readiness assessment for new product solutions is that the product development team gathers and present data, and external assessors review the material to see if the project fulfills the objectives as an input to a later gate meeting review and approval.

Discussion and Conclusion

The purpose of this paper is to analyze and discuss how the MRL scale can support the assessment of a manufacturing technology's maturity level. The assessment of the assembly system with help of a MRL scale was a first attempt to assess the maturity level in a manufacturing context at the case company. When comparing the performed assessment of the assembly system with challenges and risks found in the literature, some areas need to be discussed further.

First, according to DoD (2012) the elements being assessed, should start at a high level and flow down to the lowest component that forms the smallest unit for examination. In this case the assembly system wasn't divided into several sub-systems during the assessment. Only a high level assessment of a complete assembly system was performed. This makes it difficult to say which maturity level each sub-system had, and if the sub-systems fulfill the requirements for MRL 4.

Second, the two external auditors made individual assessments of the assembly system and their background was within pre-development of products. Their background has made them familiar with the TRL scale and how to carry out an assessment of a technical solution for the product. However, this is another context and an assessment should be performed by a subject matter expert (DoD, 2012; Bellgran and Säfsten, 2010).

Third, the definitions in the MRL framework can be interpreted in different ways and in this case the MRL scale was used for the first time at the company. It is important to have a mutual understanding between auditors and project members, regarding what is being assessed, and what is meant with each definition in the MRL framework.

When summarizing all these challenges and risks, it is difficult to say if MRL 4 was reached or not. However, this was a first attempt to use the MRL scale which contributed to an increased knowledge regarding challenges and risks at the company, when conducting a test in a prototype environment. As Bellgran and Säfsten (2010) mean, evaluation constitutes an important part of the work in manufacturing system development, and evaluation is often a neglected activity among manufacturing companies, despite its importance.

Our study shows that assessment of new manufacturing technologies is very dependent on relevant knowledge of the assessors to perform the assessment. Also, clear definitions and understanding of the assessment areas. The findings are relevant to process development managers, plant managers, and others interested in management of manufacturing processes. In particular, our discussion has underscored that assessment of new manufacturing technologies is challenging.

One limitation with this study is worth mentioning. The challenges and risks found, only builds on one single case study performed within the manufacturing industry. However, there is a lack of research studies investigating the early phases of manufacturing technology development projects (Frishammar et al., 2012). Despite, the importance of developing the manufacturing system this area seems to be neglected.

Further, pre-development and evaluation of new manufacturing technologies is necessary to become competitive on a global market. The use of the MRL scale is one way to assess new manufacturing technologies including the two important steps of testing manufacturing equipment in a prototype environment (MRL4) and testing in a production relevant environment

(MRL6). It would be interesting to repeat the assessment, but on another manufacturing technology. Even though the empirical findings are supported by well-recognized literature, there is still a need for developing knowledge about evaluation of new manufacturing technologies.

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