David A. Dornfeld
Barbara S. Linke
Editors

Leveraging Technology for a Sustainable World

Proceedings of the 19th CIRP Conference on Life Cycle Engineering, University of California at Berkeley, Berkeley, USA, May 23–25, 2012

Springer

Leveraging Technology for a Sustainable World

David A. Dornfeld • Barbara S. Linke
Editors

Leveraging Technology for a Sustainable World

Proceedings of the 19th CIRP Conference on
Life Cycle Engineering, University of California at Berkeley,
Berkeley, USA, May 23–25, 2012

Springer

Editors
Prof. David A. Dornfeld
Laboratory for Manufacturing and Sustainability (LMAS)
University of California at Berkeley
Berkeley, CA
USA

Dr. Barbara S. Linke
Laboratory for Manufacturing and Sustainability (LMAS)
University of California at Berkeley
Berkeley, CA
USA

ISBN 978-3-642-29068-8 e-ISBN 978-3-642-29069-5
DOI 10.1007/978-3-642-29069-5
Springer Heidelberg New York Dordrecht London

Library of Congress Control Number: 2012935109

© Springer-Verlag Berlin Heidelberg 2012
This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed. Exempted from this legal reservation are brief excerpts in connection with reviews or scholarly analysis or material supplied specifically for the purpose of being entered and executed on a computer system, for exclusive use by the purchaser of the work. Duplication of this publication or parts thereof is permitted only under the provisions of the Copyright Law of the Publisher's location, in its current version, and permission for use must always be obtained from Springer. Permissions for use may be obtained through RightsLink at the Copyright Clearance Center. Violations are liable to prosecution under the respective Copyright Law.
The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.
While the advice and information in this book are believed to be true and accurate at the date of publication, neither the authors nor the editors nor the publisher can accept any legal responsibility for any errors or omissions that may be made. The publisher makes no warranty, express or implied, with respect to the material contained herein.

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Preface

Welcome to the 19th CIRP Conference on Life Cycle Engineering hosted by the University of California, Berkeley! The Berkeley campus is both the University of California's flagship campus as well as a renowned research center that continues a legacy of innovation in engineering, science, society, culture, and politics. We hope that this environment will lead to a productive discussion within our Life Cycle Engineering (LCE) community.

The 19th CIRP LCE conference continues a strong tradition of scientific meetings in the areas of sustainability and engineering. The theme for this year's conference is Leveraging Technology for a Sustainable World. As resources have become increasingly scarce and the environmental impact of business and industry has grown, it has become vital for engineers to provide leadership in developing those innovations that will enable green businesses and industries that remain socially responsible and economically successful. It is our goal that this conference will serve as an international forum for researchers to review and discuss the current developments, technology improvements, and future research directions that will allow engineers to meet this societal need.

The conference includes over 100 technical papers that have been accepted after a rigorous peer review and revision process. The research covers Businesses and Organizations, Case Studies, End of Life Management, Life Cycle Design, Machine Tool Technologies for Sustainability, Manufacturing Processes, Manufacturing Systems, Methods and Tools for Sustainability, Social Sustainability, Supply Chain Management. Keynote talks will be given by Dr. Julian Allwood of the University of Cambridge, Dr. Michael Overcash of Wichita State University, Mr. Richard Helling of Dow Chemical, Ms. Karen Huber of Caterpillar, and Mr. Adam Hansel of DTL/Mori Seiki. We hope that these presentations and the proceedings will serve as a valuable source of information on the state of LCE.

We would like to thank all of the participants for their contributions to the conference program and proceedings, as well as the organizing team at the Laboratory for Manufacturing and Sustainability for their support. We would also like to extend our gratitude to the members of the Scientific Committees for their continued support in helping to make this a successful conference!

The conference program would not be possible without the generous financial support of our industry sponsors who, at the time of this writing, include: Samsung, Mori Seiki/DMG, Esprit by DP Technologies, and Dow Chemical. In addition our thanks go to the National Science Foundation NSF, who provided financial support for graduate students and postdoctoral researchers attending the conference.

Thank you again for your support of the 19th CIRP LCE conference and we look forward to a great meeting!

David A. Dornfeld
Barbara S. Linke

Organization

Chairs

Prof. David A. Dornfeld
Dr.-Ing. Barbara S. Linke

Organizing Committee

Mr. Antoine Chaignon
Ms. Yi-Fen Chen
Mr. Joshua Chien
Mr. Seungchoun Choi
Mr. Lee Clemon
Ms. Nancy Diaz
Mr. Moneer Helu
Ms. Yuchu Huang
Dr. Margot Hutchins
Mr. Daeyoung Kong
Dr. Hyunseoup Lee
Ms. Jennifer Mangold
Ms. Katherine McKinstry
Ms. Joanna Noble
Ms. Emily Rice
Ms. Stefanie Robinson
Ms. Kathy Schermerhorn-Cousens
Mr. Anton Sudradjat
Dr. Karl Walczak

International Scientific Committee

Prof. S. Ahn / KR
Prof. L. Alting / DK
Prof. F. Badurdeen / US
Prof. A. Bernard / FR
Prof. H. Bley / DE
Prof. B. Bras / US
Prof. D. Brissaud / FR
Prof. G. Byrne / IE
Prof. W. Dewulf / BE
Prof. F. Doyle / US
Prof. J. Duflou / BE
Prof. H. ElMaraghy / CA
Prof. W. ElMaraghy / EG
Prof. K. Feldmann / DE
Prof. J. Greene / US
Prof. T. Gutowski / US
Prof. K. Haapala / US
Prof. M. Hauschild / DK
Prof. C. Herrmann / DE
Prof. J. Hesselbach / DE
Prof. J. Issacs / US
Prof. I.S. Jawahir / US
Prof. J. Jeswiet / CA
Prof. H. Kaebernick / AU
Prof. S. Kara / AU
Prof. F. Kimura / JP
Prof. T. Kingsbury / US
Prof. F. Klocke / DE
Prof. G. Lanza / DE
Prof. T. Lien / NO
Prof. C. Luttropp / SE
Prof. H. Meier / DE
Prof. N. Nasr / US
Prof. A. Nee / SG
Prof. R. Neugebauer / DE
Prof. J.F.G. Oliveira / BR
Prof. A. Ometto / BR
Prof. M. Overcash / US
Prof. G. Reinhart / DE
Prof. O. Romero-Hernandez / MX
Prof. G. Seliger / DE
Prof. M. Shpitalni / IL
Prof. W. Sihn / AT
Prof. S. Skerlos / US
Prof. R. Steinhilper / DE
Prof. J. Sutherland / US
Prof. S. Takata / JP
Prof. S. Tichkiewitch / FR
Prof. T. Tomiyama / NL
Prof. J. Twomey / US
Prof. Y. Umeda / US
Prof. H. van Brussel / BE
Prof. F. van Houten / NL
Dr. A. Vijayaraghavan / US
Prof. E. Westkämper / DE
Prof. C. Yuan / US
Prof. H. Zhang / US

Exploiting Life Cycle Innovation

J.E. Parada Puig[1], S. Hoekstra[1], and L.A.M. van Dongen[1,2]

[1] Laboratory of Design, Production and Management, Faculty of Engineering Technology
University of Twente, Enschede, The Netherlands

[2] NedTrain B.V., Utrecht, The Netherlands

Abstract

Life cycle innovation is achieved by continuous technology insertion in each stage of the life cycle. For capital assets, opportunities for innovation are produced through integration, collaboration and long term partnerships. Such opportunities arise in the acquisition phase, and the client must balance product, process and supply chain decisions. To understand what is missing in the innovation chain, we present a novel life cycle model relating products and capital assets. We then provide a framework that exposes links between the asset and maintenance architectures. We believe both to be fundamental contributions for reducing uncertainty, helping collaboration in complex projects.

Keywords:

Life Cycle Model; Innovation; Architecture Framework

1 INTRODUCTION

Capital assets are complex socio-technical systems, which are engineered to provide the vast majority of services of industrialized society. These systems have long life cycles, and are known to create a particularly complex environment for managing innovation [1]. The amount of uncertainty involved makes the development and acquisition of capital assets particularly risky for the user/owner/maintainer. In such setting, collaboration and cooperation through long term partnerships can have a fundamental role in creating higher level innovations [2].

There are many common characteristics between oil refineries, chemical plants, energy plants, distribution grids, telecom networks, aerospace, land and marine transportation systems. First, billions of dollars are invested in acquiring these systems every year, in almost every country and organization in the world. However, for complex systems initial investment can represent as little as 12 - 35% of the life cycle costs. Most of the expenditure (up to 75%) occurs during operations and support [3] [4]. Second, from acquisition and contracting to the end-of-life stage such systems have a life span of 30+ years. Third, unlike typical products, which are mass produced, capital assets tend to be constructed under unique project and contractual circumstances. Many stakeholders and organizations are involved and managing relations instead of market transactions appears to be important.

Innovations can appear in such a long life span of capital assets during the original design or re-design, construction (of the asset) or overhaul, or during the utilization and support stage –once the asset is (re)commissioned. Such innovations become process innovations for the operator/owner of the asset, and can have a significant impact on the performance of the client organization.

To frame our research we present the following context. Large organizations or consortia typically construct complex capital assets. The client is a public or private organization. Assets are bought and then used to provide a public service, to manufacture products, or to perform a special function within a wider production system, such as a robot in a Flexible Manufacturing System. These assets are engineered by integrating components from a number of Original Equipment Manufacturers (OEMs). Therefore, we refer to the constructor as the systems integrator. After the development process, knowledge and information sharing is an important component in the transfer of product ownership. Therefore, collaboration through long term partnerships will have a prominent role in the effectiveness of the product when fielding assets within production organizations that use and maintain high value assets. Building long term partnerships can provide the feedback to boost innovation for the supplier.

Our research focuses on reducing the uncertainty of such projects and we take the perspective of the asset manager. Specifically, we propose a framework that builds on the work by [5-7] to show the links between two fundamental architectures: *(i)* the architecture of a maintenance factory and *(ii)* the complex asset's architecture. By exposing these links we are in a better position to understand how asset performance is influenced by design decisions and the maintenance environment.

This paper is organized as follows. In section two, we review literature on innovations associated to particular life cycle stages. Next, in section three, we explain the transition of the product ownership and the challenges involved in asset innovations that provide process innovation for the client organization. Following section three, in section four we present the structure of our research and provide a framework to relate the architecture of the maintenance factory to the asset architecture. Finally, we present our summary and conclusions in section five.

2 LITERATURE REVIEW

Innovation provides changes that make organizations, products and processes adapt to changing markets, use profiles or operating environments. Organizations can compete because innovations help them to improve quality, reduce costs, improve delivery or increase flexibility. Innovation has been linked to organizational performance, for example in sales and market share [8].

2.1 Types of Innovation

Innovation research typically focuses on either manufacturing or service organizations. For manufacturing, four types of innovations are *(i)* product innovation, *(ii)* process innovation, *(iii)* marketing innovation and *(iv)* organizational innovation [8] [9]. In the service sector, innovations have been related to the service delivery process, as this affects the types of service offerings and service quality. We continue with a brief discussion of the characteristics of each type of innovation.

Product innovation

Product innovations are improvements or new added value in terms of a product's characteristics. This value can be in the form of new specs, new functions, new components and materials, improved ease of use or customer satisfaction, increased quality or lower cost [8].

Process innovation

Process innovations happen when new technologies eliminate non-value adding activities, decrease variable costs, increase output quality or improve delivery [8].

Marketing Innovation

Market innovations produce change in any of the four key elements of placement, package, pricing or promotion. The marketing innovations translate in new package, appearance, shape and/or volume (not technical or functional), new placement (distribution channels), new promotion techniques or new pricing techniques [8].

Organizational Innovation

These types of innovations can be in the form of new routines, new procedures, new management processes, new management systems, new organization structure, new information systems or new information sharing practices. Organizational innovations have the potential of driving change within a current way of working. This in turn affects an organization's innovation capability, and has been found to be strongly related to the ability to turn innovation into performance [8].

Service innovation

Innovations in services result in improved user friendliness, improved availability, reliability, affordance with respect to maintenance, safety, sustainability or in increased speed of service production or delivery [10].

2.2 Innovating in the Life Cycle

The horizontal process of Figure 1 shows the generic life cycle of products. A typical product is designed, produced and is used/supported until it reaches its retirement age [11]. In contrast, the life cycle of capital assets, e.g. complex production equipment used by manufacturing organizations, can be extended by multiple re-design and overhaul/technology refresh (projects) stages. In practice, this happens recursively within the span of the capital asset's life cycle. The concept of the asset life cycle is shown in the spiral model of Figure 1, which is inspired on the spiral model of software development by [12]. During the utilization stage, a manufacturing asset provides the required service to make other products. This relationship between the life cycles of capital assets and the generic life cycle model of products is also represented in Figure 1. In manufacturing operations, a single asset can accommodate a part of the production (stage) for several different products before it becomes obsolete.

In a similar way as in manufacturing, capital assets are also a prime component of the processes of service industries. Therefore, innovations inserted through the purchase of capital assets become a driver of change in the service delivery process. An innovation survey conducted in 1996 found that about a quarter of all innovation investment of service companies was made on machines and physical resources [10].

Life cycle innovation is achieved by continuous technology insertion in each stage of the asset life cycle. Figure 1 shows how the asset's life cycle model accommodates all innovation types (numbers 1-4): Product innovations (1) are achieved in the design or re-design stage of capital assets. Process innovations (2) correspond to the construction or overhaul and technology-refresh programs. Marketing innovations (3) are inserted in the tendering process, when new contracting arrangements, delivery agreements and long term partnerships are made with the systems integrator and OEMs. Finally, service innovations (4) are inserted during the utilization and support stages.

3 COOPERATION IN ASSET ACQUISITIONS

Fielding a new asset is an investment in *process innovation* for the user/owner/maintainer. This makes the case of capital assets especially important. It affects all the client organizations that rely on production capacity for delivering *their* products and/or services. Asset downtime reduces production capacity, and downtime is influenced by design and by the fit of the asset to the support infrastructure. Overlooking small effects during design can have large consequences on asset performance.

3.1 Historical Perspective

In the past, industries designed high value capital products in teams, which involved the production organization (user), and the suppliers –to whom the construction was outsourced. Reliability, availability and costs were in some cases implicitly considered,

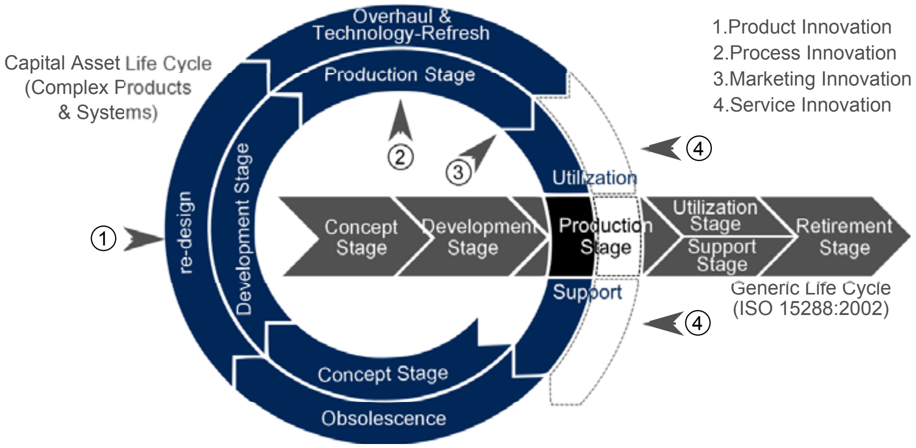


Figure 1: Innovation in the life cycle of a capital asset (spiral), and the generic life cycle of a product manufactured by the asset.

together with technical innovation [13]. For large utilities of government and defense, a strong engineering-led vision was predominant in the market until the 1990s. Large state owned companies or government agencies had in-house capabilities to specify, design and sometimes even manufacture their own assets.

Also in The Netherlands there was “a strong dominance for technology” [13]. Technical innovation was perhaps an additional objective. Traditionally, organizations specified the technical and design features, and evaluated detail design of capital assets. Construction was agreed-on with *design freezes*. Engineering offices, constructors and consultants were coordinated by the client, who had the technical expertise in fields such as civil, electrical or mechanical engineering. Maintenance mostly remained an in-house organization. In such arrangement, the role of the client was more or less that of a system integrator, as is portrayed in Figure 2*a*.

Based on the functional/technical specifications, asset construction was contracted out. After detail design was complete, the technical knowledge was received from the subcontractors via the main contractor. This provided sufficient knowledge to compile the operating and maintenance instructions based on the documentation supplied. Moreover, this also enabled solutions to teething problems before fielding equipment [13].

“Intensive collaboration with the industry at that time meant that a reliable business case could be drawn up. When implementing the project, minimal discussion was required in order to create understanding with all parties and collaborate in a goal-oriented manner. Engineers from all stakeholder organizations participated with systems integration teams during the design phase, and during manufacturing, acceptance inspections were performed at various factories. Active collaboration took place” [13].

3.2 Modern Challenges

Industrial market business practices have changed in recent years. Globalization, deregulation of markets, behavior of the organization (core competence problem), and the evolution of information technologies have been found to be main drivers outside the control of the organization [14]. As shown in Figure 2*b* large public utilities evolved from a discipline focused client, to asset manager in the chain. One main contractor now performs the system integrator’s function, and the client has the role of monitoring the asset performance. In some cases, manufacturers are responsible for all services required by their solutions. The approach of the buying organization has been to develop contracting schemes that try to bind the supplier to the promised performance. As high value capital goods have become more complex, so have management practices and the operational environment.

Today, lack of collaboration makes knowledge transfer difficult. Therefore, once the product ownership is transferred to the user/owner, innovation is compromised. In this context, collaboration between supplier organizations and support organizations can lead to product innovation that leaves room for continuous process innovation *after* transferring ownership of the asset. However, collaboration between suppliers of high value capital assets and support organizations is difficult. To achieve the shared goal of providing value to a third party client, a holistic approach to life cycle cost is needed (in place of purchase price), while providing a desired threshold for the availability of the capital goods. Some authors suggest that long term projects create a particularly complex context for managing innovation [1] and a meta-project vision has been suggested [15].

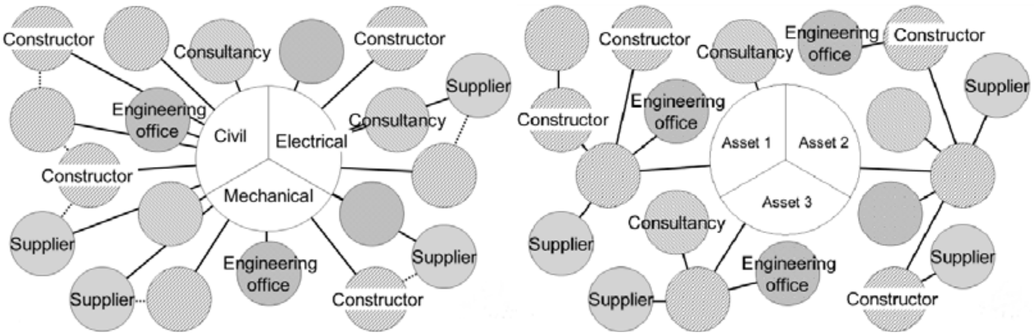
4 FRAMEWORK

To find a solution to present challenges, our research targets the reduction of uncertainty in such long term projects. We structure our research as shown in Figure 3. High level innovations have the potential to boost company performance in terms of sales and market share. Cooperation is also associated with high level innovations. Collaborative and cooperative arrangements are found in long term engineering projects which have opened new markets, and are also relied-on to share responsibility and reduce uncertainties [2]. To help collaboration with the maintenance function many authors have suggested ways to integrate RAMS information in design [16] or developing support strategies [17]. Recently focus is on information exchange through information technologies or eMaintenance [18].

High level innovation is characteristic of complexities in product and environment. This environment includes where the asset is fielded, as well as the support/operational environment of the organization. We present our research in the lower part of Figure 3, and begin by proposing a framework (this paper). Our framework intends to capture the relationship of the asset architecture and the maintenance factory architecture. Building on the framework, future research intends to help reduce uncertainty from the perspective of the support organization by modeling the relationship of asset design and the fitness for support.

4.1 Coordinating Maintenance Decisions through the Asset Architecture

Fixson [6] proposed a framework to link design decisions across three domains: *(i)* product, *(ii)* process and *(iii)* supply chain. We begin by building on this framework to better understand and position the elements of the maintenance stakeholder. The maintenance factory is the embodiment of the support environment. It is the shop floor of maintenance operations.



(a) Client as system integrator. (b) Client as asset manager.

Figure 2: Evolution of the role of large utilities (now the *client*) in the acquisitions process.

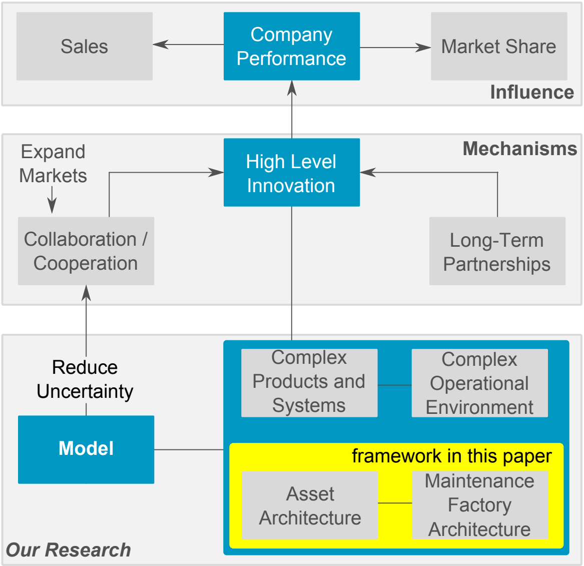


Figure 3: Our research and the framework presented in this paper.

Because of the present business practices, product domain decisions are no longer under the control of the maintenance organizations. The decisions regarding how the maintenance stakeholder will be affected by design are now the responsibility of the supplier. This is one of the greater challenges for cooperation, as these design decisions will affect the biggest share of the life cycle cost of an asset. Therefore, product domain decisions have to focus on organizing integrated product teams as well as system engineering and integration teams [19] to coordinate design decisions *with* maintenance service providers. Here, long term partnerships can play a fundamental role, and a complete design for maintenance methodology is required.

Figure 4 shows a framework for coordinating design decisions in the product domain from the perspective of the maintenance stakeholder. Because of the span and nature of the operational phase of capital assets, meeting effectiveness objectives becomes very difficult if collaboration between the asset manager and the supplier is not present. At two extremes, situations that can appear in the coordination of design are *(i)* the supplier lacks knowledge of how the system performs in the field, and in turn, *(ii)* the maintainer has insufficient knowledge on architectural characteristics, which may otherwise help to find solutions to problems presented in the field.

Decisions are made regarding the (maintenance) process domain at the strategic, tactical and operational levels. Strategic decisions are related to resource allocation, and can be summarized using, for example, the framework of Integrated Logistics Support (ILS) [3], e.g. packaging, handling, storage and transportation (PHST). Tactical decisions are made for operations planning, scheduling, and work design. On the operational level, the types of processes required to sustain the capabilities of an asset are prescribed by asset design – the asset architecture. To a large extent, the operational process flows are also determined, because they depend on component interfaces and function-component allocation schemes. When fielding a new asset, strategic and tactical decisions on the process domain are fundamentally a result of the underlying architecture of the maintenance factory. Two exceptions can be: *(i)* when a completely new organization develops from scratch, or *(ii)* when the new asset is used as a driver for complete organizational change (organization innovation).

Supply chain domain decisions affect the maintenance logistics organization. These decisions comprise assortment management, demand forecasting, parts returns forecasting, supply management, repair shop control, inventory control, spare parts ordering and deployment [20].

The framework in Figure 4 represents the problem of coordinating decisions when transferring asset ownership, when the asset enters the utilization/support stage. Fixson [6] proposed a similar framework building on the definition of modular-integral product architectures proposed by Ulrich [5]. Next, we extend these definitions in our framework to relate the asset architecture to the maintenance factory architecture.

4.2 A Framework to Relate Two Architectures

The information required for decision making in the support phase of capital assets is driven by both the asset architecture and the architecture of the maintenance factory. In Figure 4 we present a framework to relate both architectures. On the one hand, the fundamental elements of the asset architecture are *(i)* components, *(ii)* interfaces and *(iii)* functions. Firstly, components are material or software entities, which connect through an interface. Secondly, functions reflect the purpose of a *(i)* system, *(ii)* a system component, or *(iii)* an interface. Finally, interfaces reflect how the (sub) systems or components are coupled, and represent the boundaries between system functions. Interface reversibility in [6] is directly related to asset maintainability.

Maintainable components of a system are those that can be subject to a maintenance operation. However, the end goal of the maintenance operation is to restore the system function, not the component. Therefore, the function-component allocation plays a fundamental role. When analyzing maintenance operations, the functions can be grouped in different ways; for example, critical functions, secondary functions, redundant functions, control functions, safety functions, protection functions.

The factory architecture, on the other hand, can be characterized by *(i)* resources, *(ii)* flows and *(iii)* operations. We use this definition extending the work by [7]. This is, to the best of our knowledge, the description found in the literature that most closely relates to our research focus. Resources represent material and nonmaterial entities that are consumed by operations. These can be parts, facilities, tools and equipment, manpower, data and computer hardware.

Operations represent conversion activities. An operation is a specific action to be performed by a resource entity, analogous to what a function is to a component –or an interface– in the asset architecture. Maintenance operations or actions can be described in a similar way as basic operations of a factory, such as milling, welding or assembling. Typical maintenance operations involve overhaul, replace, repair, inspect, test, lubricate, correct, clean, replenish, adjust, discard, check, remove, install, connect, disconnect or tighten.

Flows are transitions that occur to resources and operations. These transitions relate both resources and operations with themselves and with each other. Flows represent the dynamics of a maintenance factory in the sense that they reflect information transfers or material movements. We therefore use the definition of resource flows and operation flows. Again, for analogy, we suggest that flows are to the factory architecture as interfaces to the product architecture. The environment links both architectural descriptions of the asset and the factory, and represents where the asset is fielded for operational use. We propose the framework in Figure 4 to better understand the consequences of design decisions on product, process and supply chain of the maintenance factory. Because our architectural descriptions are analogous between the (asset) product

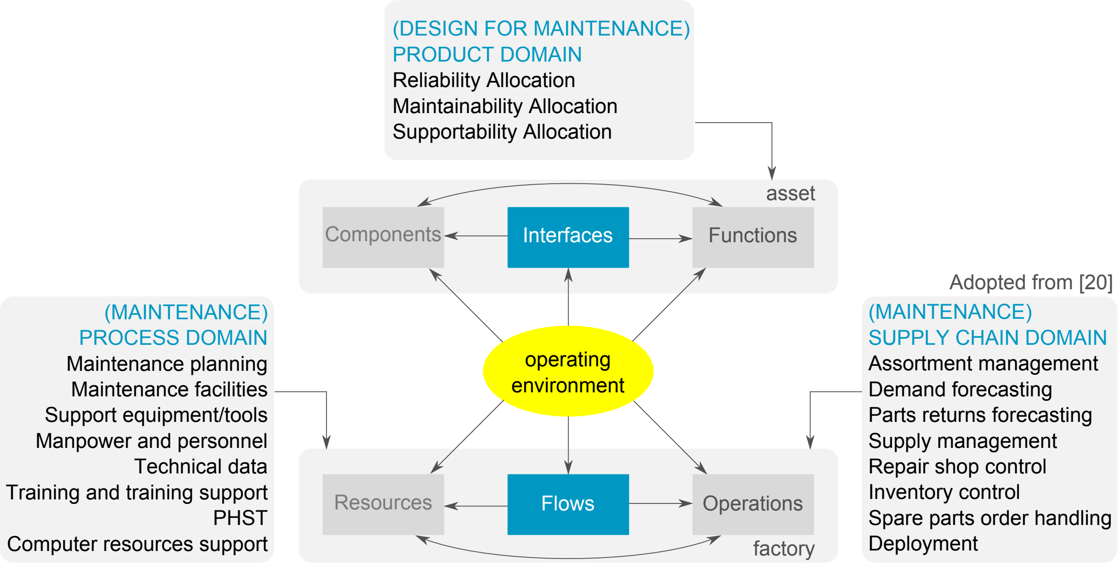


Figure 4: A framework to relate the asset architecture and the maintenance factory architecture.

and the factory, describing their relations can become less complicated. We show this in the next subsection by means of an example.

4.3 A Working Example

Using our framework, we present in Figure 5 an extension of Ulrich's example of a trailer [5] using Fixson's descriptions of functions, components and interfaces [6]. Trailer 1 (left) has modular-like function-component allocation (FCA) styles. Trailer 2 (right) has functions, such as "support cargo", which have integral-complex FCA schemes. Each layer is a decomposition of the product. Each vertical arrow represents the mapping of each decomposition to the next. The component decomposition represents component-interface relations. The functional decomposition represents function-interface relations. The operation decomposition represents operation-flow relations. Finally, the resource decomposition represents resources-flow relations.

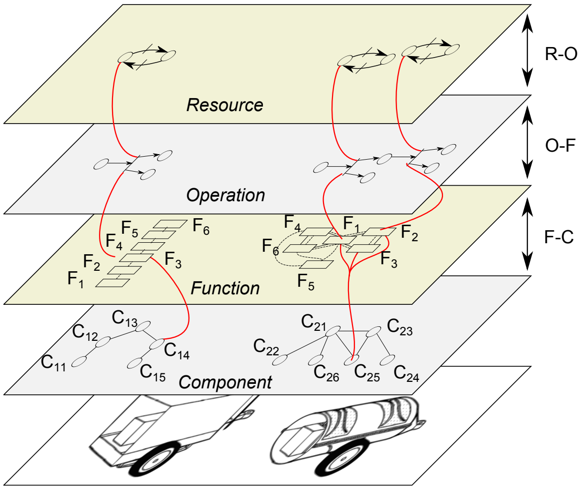


Figure 5: Decompositions of an example product and the mappings of components, functions, maintenance operations and maintenance resources.

The mapping from function to component (F-C) is the function-component allocation scheme [6]. The operation-function (O-F) allocation mapping determines what activities are performed to restore which function. The resource-operation (R-O) allocation mapping determines which resource is consumed by which operation.

In the modular-like architecture of Figure 5, maintenance operations can be triggered, for example, by functional failures. The failure cause of a functional failure is the mapping to the (lower) component decomposition. To correct the failure a maintenance activity is performed. Typical maintenance operations are compound activities. A typical higher level operation for systems that are repaired by replacement consists, for example, of a remove, install and tighten sequence. Let us assume the functional failure (FF) of the higher level function F_3 which corresponds to "connect to vehicle" [6], shown in Figure 5. Therefore, the replace sequence (operation-flow) should be linked to the components that provide the function connect to vehicle. Therefore, at the architecture level the interfaces of component C_{14} should be reversed to repair the function F_3. These are the interfaces between the hitch (C_{14}) and the box (C_{13}), and between the hitch (C_{14}) and the fairing (C_{15}). Resources such as manpower, tools, spares and equipment will be required (resource-flow). The resource-operation allocation is the mapping required to estimate the impact on the support architecture.

4.4 Significance

Our framework extends existing work and considers a more specific match of maintenance factory operations and the product architecture. The product being a capital asset in our case of interest, and operations being particularly focused on the jobs required to maintain the asset. Asset supportability is the fit between both architectures, and is measured in terms of asset downtime –caused by queuing for the resources of the maintenance factory. Our modeling approach in future research will build on this framework.

5 SUMMARY

In this article, we have contrasted the generic life cycle model of products and a spiral model for capital asset life cycle. This has helped to better visualize innovations in the life cycle of capital assets. We then placed emphasis on the transition of product ownership from the supplier of capital assets to the user/owner/maintainer. In such complex projects, sharing knowledge and collaboration between stakeholders appears to be beneficial. Collaboration is fundamental because it can streamline information sharing, builds trust and strengthens supplier partnerships. High-level innovation can be achieved in such collaborative environments, and this can benefit the product, process and supply chain of the asset operator/maintainer.

To help collaboration between suppliers and client organizations we target the reduction of uncertainty in complex engineering projects. For such purpose we have provided a framework that relates asset supportability to architectural design attributes of complex systems. Our framework positions the research on the links between (i) the maintenance factory architecture and (ii) the capital asset's architecture. We will use this framework in future research to strengthen knowledge about the interfaces between design and the (support) maintenance operations. We believe this to be a way forward in making more transparent supplier-buyer relations and problem solving when fielding capital assets.

6 ACKNOWLEDGMENTS

This research is part of the “Rolling Stock Life Cycle Logistics” applied research and development program, funded by NS/NedTrain. The Maintenance Engineering chair of the Laboratory of Design Production and Management at the University of Twente is funded by the Loyd’s Register Educational Trust. The Lloyd's Register Educational Trust (The LRET) is an independent charity working to achieve advances in transportation, science, engineering and technology education, training and research worldwide for the benefit of all.

7 REFERENCES

[1] Alderman, N., Ivory, C.J., McLoughlin, I.P., Vaughan, R. (2005): Sense-making as a process within complex service-led projects, in: International Journal of Project Management, Vol. 23, No. 5, pp. 380-385.

[2] Tether, B. (2002): Who co-operates for innovation, and why An empirical analysis, in: Research Policy, Vol. 31, No. 6, pp. 947-967.

[3] Jones, J.V., (2006): Supportability engineering handbook: implementation, measurement, and management, McGraw-Hill, New York.

[4] Ellram, L.M. (1994): A taxonomy of total cost of ownership models, in: Journal of Business Logistics. Vol. 15, No. 1, pp. 171-192.

[5] Ulrich, K. (1995): The role of product architecture in the manufacturing firm, in: Research Policy, Vol. 24, No. 3, pp. 419-440.

[6] Fixson, S.K. (2005): Product architecture assessment: a tool to link product, process, and supply chain design decisions, in: Journal of Operations Management, Vol. 23, No. 3/4, pp. 345-369.

[7] Hayes, R.H., Wheelwright, S.C., Clark, K.B. (1988): Dynamic manufacturing: creating the learning organization. The Free Press, New York.

[8] Gunday, G., Ulusoy, G., Kilic, K., Alpkan, L. (2011): Effects of innovation types on firm performance, in: International Journal of Production Economics, Vol. 133, No. 2, pp. 662-676.

[9] Utterback, J.M., Abernathy, W.J. (1975): A dynamic model of process and product innovation, Omega, Vol. 3, No. 6, pp. 639-656.

[10] Hipp, C., Grupp, H. (2005): Innovation in the service sector: The demand for service-specific innovation measurement concepts and typologies, in: Research Policy, Vol. 34, No. 4, pp. 517-535.

[11] International Organization for Standardization (2008): Systems engineering - System life cycle processes, in: ISO/IEC 15288:2008.

[12] Boehm, B.W. (1988): A spiral model of software development and enhancement, in: Computer, Vol. 21, No. 5, pp. 61-72.

[13] van Dongen, L.A.M. (2011): Maintenance Engineering: Maintaining the Links, in: Inaugural Lecture on appointment as Chair of Maintenance Engineering, University of Twente.

[14] Cova, B., Salle, R. (2007): Introduction to the IMM special issue on ‘Project marketing and the marketing of solutions’ A comprehensive approach to project marketing and the marketing of solutions, in: Industrial Marketing Management, Vol. 36, No. 2, pp. 138-146.

[15] Alderman, N., Ivory, C.J. (2010): Service led projects: understanding the meta-project context, in: Construction Management and Economics, Vol. 28, No. 11, pp. 1131-1143.

[16] Markeset, T., Kumar, U. (2003): Integration of RAMS and risk analysis in product design and development work processes: A case study, in: Journal of Quality in Maintenance Engineering. Vol. 9, No. 4, pp. 393-410.

[17] Markeset, T., Kumar, U. (2005): Product support strategy: conventional versus functional products, in: Journal of Quality in Maintenance Engineering, Vol. 11, No. 1, pp. 53-67.

[18] Candell, O., Karim, R., Söderholm, P. (2009): eMaintenance—Information logistics for maintenance support, in: Robotics and Computer-Integrated Manufacturing, Vol. 25, No. 6, pp. 937-944.

[19] INCOSE (2010): Systems engineering handbook. A guide for system life cycle processes and activities, INCOSE, Seatle, USA.

[20] Driessen, M.A., Arts, J.J., van Houtum, G.J., Rustenburg, W.D., Huisman, B. (2010): Maintenance spare parts planning and control: A framework for control and agenda for future research, in: Beta Working Paper, No. 325.