NordDesign 2012
August 22 – 24, 2012
Aalborg, Denmark

Factors Affecting to Exploitation of Modularity

Jouni Lehtinen
Cargotec Finland Oy
jouni.lehtinen@cargotec.com

Timo Lehtonen
Tampere University of Technology
timo.lehtonen@tut.fi

Tero Juuti
Tampere University of Technology
tero.juuti@tut.fi

Asko Riitahuhta
Tampere University of Technology
asko.riitahuhta@tut.fi

Abstract

Utilizing the benefits of modular products is an industrial phenomenon that has emerged in second quarter of 20th century. This was made possible by developments in manufacturing technologies such as standardized quality of materials, tolerance levels and methods that enabled benefits through repetition. There are many examples in history where modular products have turned out as success stories. Equally, there are many examples of modular product that have never proceeded beyond prototype stage and have ended up as commercial failures.

In this paper we discuss the factors that affect to exploitation and success of modularity. In previous research several factors, based on business and technological issues alike, have been presented. However, these factors do not really explain the success or failure of cases presented in this paper which represent equipment in capital goods sector; locomotives with electric traction, bus manufacturing and shipbuilding. These cases are explored with two questions in mind: is the size or weight of the products limiting modular approach and are the factors effecting modularity due to internal product characteristics or external properties such as business environment?

In our conclusion we present that the ruling factor affecting modularity is the existing business environment. However, increased size of products typically has effect to manufacturing technologies due to challenges in tolerances and required investment to manufacturing facilities thus requiring manual work which hinders repetition in manufacturing and modularity benefits.

Keywords: modularization, historical perspective, market environment.

Introduction

It can be said that modularity related to product architectures has first arisen during certain era in history. In the past, ability to exploit modularity in products has been limited by required manufacturing capabilities: materials with standardized quality, adequate level of tolerances and industrial methods that enable benefits out of repetition in manufacturing. Such production environment is not an axiomatic state if we consider issue in historical perspective. However, at present it is possible to achieve all above mentioned manufacturing capabilities in all major technology areas. Despite this, when it comes to manufacturing of heavy capital goods (e.g. industrial machinery or transportation equipment), modularity is exploited very inconsistently. In this paper we discuss the factors that enable or hinder modularity in manufacturing of capital goods sector equipment.

Method

First we provide a background for the development of modularization over time with historical review. This review will show that in past modularization has been presented as solution and used widely in context of capital goods. However, it can be seen that this hasn't certainly made modularity the dominant method.

Second, we present two research papers from application areas where modular solutions can be said to be dominant. These application areas are electronics industry VLSI circuits in particular and consumer electronics. Although these research papers describe factors effecting modularity, we conclude that these findings do not readily explain observations that can be made in area of heavy capital goods.

Third we present three case examples about modular electric locomotives, modular buses and modularity approaches in shipbuilding. In here we explore two topics:

> *First, does the physical size really matter? Is the modularity within a locomotive somehow different from electric circuit or consumer electronics due the weight and size of the proposed modules?*
>
> *Second, are the factors effecting modularity due internal product characteristics or are the external properties e.g. behavior in business environment more dominant?*

These questions are interconnected thru our case material.

History of Modularization

Using modules in products and utilizing the benefits from modular structures are solutions developed in practical design work in the industrial history of the 20th century. Products labeled modular in the industry share the fact that they feature an internal division or divisions based on some more abstract reason than the general component structure. This more abstract reason is generally related to the organizing of production, to the life cycle or the configurability of the product.

Even in the remote history we can find products that feature at least the ideas of the Baukastensystem defined by Borowski [1]. However, it may be impossible to indisputably show the first modular product in the world. For the scope of this paper, we do not need step back in time further than to the year 1939.

At that time, a diesel engine with a modular architecture was introduced in an American patent. Baldwin Locomotive Works applied for a patent on 27 February, 1939 (U.S. Patent No. 2249628, granted 15 June, 1941) for a 4,000hp diesel engine with six engine generator modules. The advantage of this structure was the opportunity to use different power ranges in trains of different weight by starting and stopping the engine modules as necessary. Later, the firm applied for a new patent for a locomotive with eight engine modules (U.S. Patent No. 2317849, granted 27 April, 1943). A prototype engine was built, but it was not finished due to the lack of buyers. The US railroad companies solved the issue of changing traction force in another way. A necessary number of smaller engines – up to five locomotives – were linked to the train, and electrical steering enabled the same two-man crew steering from the first locomotive. [2]. *[Brown 1982]*

Our second example takes place between 1943-45 in the Blohm & Voss, AG Weser, and Schichau Werft shipyards. These shipyards manufactured submarines in serial production under a considerable wartime pressure. To boost production, a modular submarine of the type XXI was developed. In this case, modularity referred to dividing the hull of the submarine in longitudinal blocks. These blocks could be manufactured outside the basin. In principle, the final assembly time of the submarine was reduced to 176 days. This is a classical example of a reason to divide the product into parts to meet the requirements of the organization of production. Large production numbers, however, were not achieved due to external reasons, primarily the air raids of the US Air Force. Only 133 XXI type submarines were started to build during war. However, US Navy became familiar with this new method and it was considered to be applied also in US naval shipyards. However, the investments were rejected as US Navy Department could not guarantee adequate funding for the required investments in peacetime market situation [3, 4]. The method was fresh at that time and it is still used one way or another in shipbuilding.

Our third example relates to managing product variation and implementing configurations via modular solutions. In 1980, the Swedish truck and bus manufacturer Scania introduced a new model line, the so-called Series Two. Compared to the previous models, the novelty was the advanced standardization of structural elements. This created a prerequisite for the implementation of modular solutions in Series Three in 1987. [7, 8] The structural changes considerably rationalized the products [9]. While the numbers of necessary parts and tools were considerably reduced, (for example, from 1,600 to 280 in sheet metal tools) Scania's cabin variations extended. In this case, modularity was pure assembly modularity, perhaps even standardization in part.

In conclusion, modular product is an industrial innovation and as such at least 73 years old. There are different kinds of modularity depending on the respective aims of design and there exist companies and products whose success can be considered as a direct result of using modular structures. However, not all modular experiments have been success stories.

Previous research of factors effecting modularity

Schilling has presented a general theory about the factors that drive technical systems towards increasing or decreasing modularity. According to Schilling’s model following (direct) factors have effect of increasing modularity: differential capabilities among competing firms, diversity in technical options, customer heterogeneity in desired function of scale, speed of technological change and competitive intensity. On the contrary, modularity should decrease if: greater functionality is achieved through component specificity (integral architecture is more efficient), customers have difficulties to assess component quality and interaction and if it’s difficult for customers to assemble system. [10] Schilling grounds her theory on observations from personal computers, home appliances, software and bicycles.

Schilling’s theory may be accurate with mass produces commercial goods, however, according to authors’ experience, most factors presented by Schilling work just the other way around when it comes to products in capital goods sector and especially in project based industries. First of all, differential capabilities among competing firms, diversity in technical solutions and customer heterogeneity all increase variation in product architectures and efficiently prevent emergence of dominant design and standard solutions. Since modularization in capital goods sector is highly dependent on reasonable level of standardization, the effect of above mentioned factors is opposite to what Schilling claims. In addition, increased competitive intensity has similar effect thus hindering modularization. The main reason behind different effect of same factors for modularity between mass production and projective manufacturing of capital goods is due to the reason why modularization is applied. In mass production, modularity is applied to increase variety efficiently. In projective manufacturing, modularity is applied to decrease variety without loss of ability to serve each customer with customized solution.

Whitney has covered the same question about factors that promote or hinder modularity. The claim is that certain products can be designed as modular architectures and others not because the absolute level of power needed to operate the system. In his paper Whitney concentrates on comparison of Very Large Scale Integration (VLSI) and "complex electro-mechanical-optical" (CEMO) products (microchips being example of former and traditional mechanical solutions e.g. jet engine of latter). According to Whitney, in VLSI products system design and device design can be decoupled and the result is that VLSI systems can be designed with dramatic reduction in cost and product development time. What comes to design of products of CEMO category, it's claimed that similar decoupling of design stages doesn't exist except for standard fasteners and fittings. Thus, system and device design processes are integrated which means that each part is designed specifically for each product. Whitney continues to rationalize the differences by high level of power carried and processed by CEMO compared to VLSI product (that transfer only information not significant power), level of accepted tolerances (can be bigger in VLSI) and elimination of side-effects (important in CEMO). [11]

Whitney's claims have reasoning if products are reviewed only from engineering design point of view. However, it seems that modularity potential cannot be treated only as engineering paradigm. According to authors' experience many CEMO products have changed from integral to modular architectures over a time as a result of need to reduce costs and time in delivery process. This indicates that most equipment can be designed modular (still fulfilling the customer's requirements). However, this requires that enough repetition is achieved in design, manufacturing and other internal or external processes that will cover the possible negative effects that come with modularity.

All in all, Schilling's focus has been only to mass produced products and most of conclusion are not applicable for industrial equipment. On the other hand, Whitney has concentrated only to engineering issues and forgetting the market environment that effect to exploitation of modularity.

Case: Locomotives with electric traction

As presented in the history chapter, the modularity is well known product structuring method in the area of railway locomotives. It has been used to achieve adaptability without success as in the Baldwin case and for facilitating the maintenance with success. During the 1980's there where attempts to develop modular locomotives, which would eventually form a basis for variant locomotive product family.

One of these was diesel-electric locomotive developed by Transtech. [12, 13] It was sold to Finnish State Railways and was offered at least to Swedish track maintenance authorities and Norwegian State Railways. Invitations for tender for the new, general-purpose diesel locomotive were sent in 1982. The actual agreement for purchase to Finnish State Railways was made on 16 November, 1983. The new locomotive was designed and manufactured as modular. The locomotive consisted of approximately 30 big constructional elements of which some were called modules. [12] This locomotive is typical example of modularization strategy where an optimal configuration is first developed as the base model and the following versions are variations of it. In research made with Swedish road vehicle manufacturing industry, this strategy was complex to maintain and there were difficulties to retain common base model, since the variety between the different variants was growing too large. There were also quality problems and problems with weight were also observed. As conclusion for the results for this strategy were stated to be a low degree of shared product architecture and costly variety creation. [14] The negative aspects observed in the Swedish research did materialize in the locomotive project. Only initial series of 23 locomotives was manufactured and there were no further sales. From the product development point of view, it was a dead end development and model did not have successor.

In the 80's the market of locomotives was very much buyers market. The customers were mighty national railways who were in position to set the requirements for the locomotives. The orders could be considerable size, at least tens of locomotives, but more often a series of hundred or more. In this situation, the development of one optimal base model (for prime customer) and developing variants for others was obvious solution. But it came with – at least with hindsight – obvious problems. For example Siemens, had to buy back its locomotives after the Norwegian State Railways (NSB) cancelled the agreement. The agreement on the delivery of 10 locomotives was signed on 23 November, 1992. The first of these Di 6 locomotives entered the test run phase in Norway in 1996. The problems with the new locomotives started immediately, and eventually NSB and the supplier cancelled the agreement in the spring of 1999, as the locomotives did not meet the requirements. [15] The locomotive in question was originally developed for Danish State Railways.

After millennium the European railway industry has changed a lot. The sole domination of the state railways has ended and way to smaller independent companies has opened. This has changed the situation such that there is more than one modular electric locomotive product that has been successfully sold to multiple customers. Three variant locomotive families from Siemens (Vectron), Alstom (Prima II), Borbardier (Traxx) are now sharing European market. However it seems to be evident that modularization strategy here is still base model with limited amount of variation. The product offering has not been changed, but the market situation and standardization has become more acceptable as customer manufacturer ratio has increased. Vossloh offers locomotive family in which there are diesel-electric and diesel-hydraulic locomotives made out of same platform. This must be considered as a significant change of thinking or technical breakthrough, because earlier these types were significantly different. This family is product architecture based and has common set of modules. The Vossloh calls modules in German "baukasten", which is like a déjà-vu of one classic book of research on modularity "Das Baukastensystem in der Technic" from year 1961 [1,16], which proposes of utilizing just this kind of product architecture in variant products.

There seems to be no restriction to utilize modularity what comes to size, weight or manufacturing facility requirement within locomotives. Therefore, the change in locomotive technology itself cannot explain the emerged exploitation of modularity. In 20 years the amount of locomotive manufacturers has decreased and number of operators capable of buying new locomotives has multiplied. This change in business environment has turned modular variant locomotive to market dominant alternative. At this moment it seems that only one remarkable manufacturer has not yet entered the modular locomotive paradigm. The buyers are becoming more and more aware of potential hidden cost of one a kind solutions.

Recently for example VR-Group (former Finnish State Railways) has ruled out tenders from manufacturers who would develop their locomotive just for this contract. The locomotive business in Europe has really gone modular.

Case: Modularity with bus manufacturing

In the manufacturing of buses, the core competence has been and still is building and furnishing the bus body. This is very labor intensive work. The yearly amount of new buses and coaches is a small fragment of amount of trucks. Customer tailored products are still very much a norm in bus and coach manufacturing and series of completely similar buses tend to be short. It is not uncommon that heavily customer tailored buses are manufactured as series of one!

During 1970's and 80's it was widely believed that bus industry will develop towards mass production paradigm. There were several costly projects of building up real "bus factories" capable to efficient serial production utilizing assembly lines. 1968 British Leyland had made decision for developing a standard bus-model and building a completely new factory with capacity to build 2000 buses per annum. The construction works of the new factory started in 1970 and in 1975/76 the factory rolled out thirty buses per week. The buses were assembled in similar line as cars. However it was a failure - the specifications of the standard bus were too restrictive and the factory was never utilized with its full capacity. Workington factory was closed in 1993. [17] Daimler-Benz AG made an investment of almost similar size when it build a new bus assembly facility at Mannheim in 1984. The DBAG factory was more flexible than Leyland's facility having 48 assembly stations on five rows. The factory was capable of building different types of buses in mixed order. With 55 minutes station cycle time the factory had theoretical capability to roll out 40 buses week when working in one shift. [18] Although this investment was successful to Daimler-Benz, it did not change the bus market in Europe.

Leyland buses can be claimed to be modular and also DBAG relied on large scale use of pre-assemblies. The modularity in itself is no stranger in the field of bus manufacturing. For example in 1955 Henschell started manufacturing of a bus model, which body structure was divided in seven independent modules. [19] However this did not give any competitive advantage and this bus remained as an experiment and curiosity. In 1978 there was a serious attempt to develop a modular bus chassis. Finnish manufacturer Sisu launched product family with name "Moni-Sisu" (Multi-use Sisu). The same chassis could be used building a bus, a mobile shop, mobile library, fire engine, delivery truck, garbage collector truck. [20] This product did not succeed well due it optimality was so much below average on most of its applications.

Within last ten years period, the importance of modular construction method seems to have increased significantly within bus manufacturing. The modularity principles in truck production at Scania have been taken in use also in Scania's bus production. Also the independent like Lahden Autokori in Finland and Higer in China, who are manufacturing buses for Scania have adapted the modular methodology in their production. Dutch Bowa presented their revolutionary bus model "Magic" in 1999. Magic had very advanced modular structure, where the front part of the bus was made ready and assembles after the seats had been carried in. The successor of this model VDL Futura is still made with this method and the building the front part of the bus as a module has been adapted at least by Scania and Volvo in some of their products. Volvo introduced a modular bus chassis in year 2000. This product family was called TX-platform and it included major layout variations having both middle and rear engine configurations. Due to company mergers, Volvo had two different city bus products with two construction methods until 2011. When they finally decided introduce same method on their factories in Sweden and Poland, they chose the modular construction alternative and the non-modular became history despite its other virtues. [21] We are at the edge that it could be claimed that modularity is an essential characteristic for up to date bus body construction. Size, weight or lack of manufacturing facilities is not restricting the use of modularity. Benefits of modularity are not big enough to help big players to overcome small manufacturers within current competitive environment. This is due to short manufacturing series which favors manual work.

Case: Modularity in shipbuilding

Merchant ships are typically built in series from one to dozens, however actual series manufacturing doesn‘t exists as all modern shipyards build many ship series at same time over long period of time. After the ships design is completed the actual shipbuilding process starts when steel plates are cut as by computer aided machines and welded together by robotized, semi-automatic or manual welding technologies in parts manufacturing face. This is followed by pre-assembly of steel blocks, painting and assembly of erection blocks. Finally the erection blocks are assembled together as complete ship in dry dock basin or slipway. Apart from massive equipment required for lifting and transportation of ship blocks the actual assembly is still very labor intensive work. Furthermore, while the overall structures are very big the required accuracy is high. [22]

Use of modularity in ship design and ship building still isn‘t very common with the exception of a few European ship design companies [23]. One reason behind this is that manufacturing of merchant ships exploits technology that doesn't enable real benefits out of repetition. Even in situation that every typical size and type of merchant ship (e.g. 12000 TEU container ship) would be identical, existing manufacturing process might not offer sufficient efficiency that would cover unavoidable drawbacks; reduced ability to make customer specific variations. Furthermore, the investment required for manufacturing process and equipment that would promote modularity in shipbuilding with current product technology could turn out insuperable within current oversupply in shipbuilding. This obstacle was identified earlier in this paper: Challenge with required investment to manufacturing equipment prevented the use of modularity when submarine XXI invented by Germans never made it‘s breakthrough in United States after Second World War. Therefore, it took decades until the block manufacturing finally became the dominant shipbuilding method.

Second and by far most crucial obstacle in exploitation of modularity in shipbuilding relates to existing business logic and market situation. The situation is bit similar than with European locomotive industry in the 80‘s. Shipbuilding has been, and still is, buyers market due to constant over capacity in shipbuilding (apart from occasional peaks in demand). This market situation has maintained and fostered the ship owner's role as definer of technical solutions. As a consequence every ship or ship series is designed as unique for certain customer [24] instead of shipyards offering standard or modular solution designed for certain customer segment and function. Airliner manufacturing serves as an interesting industry for comparison to shipbuilding. The radical consolidation in airliner manufacturing has ended up into a situation of only two major and few smaller players exist. This is an interesting comparison to shipbuilding - in China only there were approximately 430 shipbuilding enterprises in 2006 [25].

In shipbuilding, size and weight seems to start restricting exploitation of modularity. However, the ruling factor in shipbuilding is the current competitive environment leading to short series and lack of serial manufacturing practices. Despite few long standard series in shipbuilding history, (e.g. Liberty Ship and SD14) [26, 27] modularity has not become a relevant method.

Conclusions

The case examples in history (locomotive with modular engine, modular sub-marine construction and modular trucks by Scania) show that modularity has been used for a long time to organize the production, manage the products life cycle or to enable product configurability. However, not all modular products have been success stories at least from commercial point of view.

The reasons behind success or failure and the question why modularity always doesn't work have been discussed in Schilling's and Whitney's research. However, their conclusions about factors effecting modularity didn't provide sufficient explanation why certain products have turn into modular solution while others have more integral or one-of-a-kind product architecture. Schilling's outlook that the result is mainly up to existing market environment and customer behavior is probably right, despite the fact that identified factors work very differently whether modularity is applied in world of consumer goods and mass production or capital goods and projective manufacturing. On the other hand we couldn't find clear signs for Whitney's conclusion that modularity is easier to apply in certain equipment due to smaller amount of transferred power (among other technical reasons).

When the locomotive and bus examples are examined more specifically, it can be seen that products itself have stayed more or less the same but change in market environment has caused use of modularity. Here we can make a conclusion that in these cases modularity exploits potentials that can be achieved only through changes in market environment. Furthermore, it seems that the production techniques or investments in manufacturing facilities seem not to be the restricting factor in products with weight 10 (small bus) to 180 tons (octagon platform locomotive) and length from 10 (small bus) to 23 meters. However, we can see that the size of products have effect to exploitation of modularity due to tolerances and investments to manufacturing equipment. This is the case in shipbuilding. Our past experiences within modularization projects have given an impression that there exist differences in utilizing modularity in small and large size products. However, within this paper we cannot specifically define the physical size (weight or dimensions) that starts to hinder modularization – it seems to be somewhere between size of an airliner and average merchant ship. Even huge process plants have been delivered as pre-fabricated modules, [28] however the economical module weight is stated to be hundreds of tons whereas in shipbuilding, modules (blocks) are often weighted in thousand ton scale.

We hereby present that ruling factor effecting to exploitation of modularity is the competition environment which has direct effect to company, equipment and solution specific production volumes and bargaining power of the equipment manufacturer. However if size of the product exceeds certain level it will hinder modularity as repetition cannot be achieved with existing manufacturing technologies.

References

[1] Borowski, K., H., “Das Baukastensystem in der Technik”, Springer-Verlag, 1961.

[2] Brown C.A., “From Essl’s effort to Seboard’s solution”. Trains Vol.42, No7., Kalmbach Publishing Co, 1982, pp. 38-45.

[3] Williamson G., “Wolf Pack – The story of the U-Boat in World War II”, Osprey Publishing, Wellingborough (UK), 2005, ISBN 1-84176-872-3.

[4] Weir G. E., “Forged in War – The Naval-Industrial Complex and American Submarine Construction, 1940-1961”, Brassey’s, Washington, 1998, ISBN 1-57488-169-8.

[7] Sandell Kaj (ed.), Streiffert Bo (ed.), ” Scania kautta aikojen”, Streiffert & Co Bokförlag HB, Stockholm, 1990, ISBN 91-7886-058x.

[8] Lindh Björn-Eric, ”Scania and its Vehicles 1891-1991”, Streiffert & Co, Stockholm, 1992, ISBN 91-7886-075-X

[9] Erixon, G., “Modular Function Deployment – A Method for Product Modularisation”, Kungliga Tekniska Högskolan, Stockholm, 1998.

[10] Schilling M. “Toward a General Modular Systems Theory and its Application to Interfirm Product Modularity”. Academy of Management Review, Vol.25, No.2., 2000 pp. 312-334.

[11] Whitney, D. E., “Physical limits to modularity”. Working paper, ESD-WP-2003- 01.03-ESD, Massachusetts Institute of Technology, Engineering Systems Division, 2004.

[12] Pentikäinen P. P., ”Iso Vaalee”, Petrin Viestintä, 2006, ISBN 952-92-0413-2.

[13] Lehtonen T., “Designing Modular Product Architecture in the New Product Development”, Tampere University of Technology, Tampere, 2007.

[14] Holmqvist T., “Managing Product Variety through Product Architecture”. Dissertation. Göteborg: Chalmers University of Technology, 2004.

[15] Næss S., ”Di 3 – Billedboken om en loklegende” pp. 138-139 ”Da det meste gikk galt – Di 6”, BSN Forlag, Norway, 1999.

[16] Vossloh Locomotives GmbH, Product Leaflet 2012.

[17] Jack D., “Beyond Reality Leyland Bus – the twilight years”, Venture publications, Glossop (GB), 1994.

[18] Omnibus Journal number 2 1984, “A milestone in bus assembly”, Daimler-Benz AG.

[19] Regenberg B., “Die Deutschen lastwagen in der wirtsvhaftswunder zeit. Band 3: Omnibusse”, Verlag Walter Podszun, Brilon (DE), 1988, 1996 (2nd edition), pages 124-125.

[20] Oy Suomen Autoteollisuus Ab, Sisuviesti-magazine 2/78, Product leaflet printed in 1978, technical specification issued 26.12.1977.

[21] Lehtonen T., several articles in Finnish Bussiammattilainen (Bus Professional) – magazine; 6/2007 (Producton methods at Lahden Autokori), 1/2012 (Producton methods at Higer), 4/2011 (Producton methods at VDL), 3/2010 (Volvo TX Platform), 5/2011 (Volvo city buses modular body building).

[22] Kim, H., Lee, J., Park, J., Park, B., Jang, D. “Applying digital manufacturing technology to ship production and the maritime environment”. Integrated Manufacturing Systems, Vol.13, No.5, p.295-305, 2002.

[23] Erikstad, S. O. “Modularisation in Shipbuilding and Modular Production”. Working paper, IGLO-MP2020, Norwegian University of Science and Technology, Department of Industrial Economics and Technology Management, 2009.

[24] Stopford, M. “Maritime Economics”. Routledge, 2009, ISBN 0-203-89174-0

[25] OECD. “The Shipbuilding Industry in China”. Working party on shipbuilding, C/WP6(2008)7/REV1, 2008.

[26] Elphick, P. “Liberty. The Ships That Won the War”. US Naval Institute Press, 2006, ISBN 978-1591144519

[27] Lingwood, J. “SD14 The Full Story”. Ships in Focus Publications, 2004, ISBN 978-1901703641

[28] Haas, C., Fagerlund, W. “Preliminary Research on Pre-assembly, Modularization and Off-site Fabrication in Construction”. A Report to The Construction Industry Institute The University of Texas at Austin, The Department of Civil Engineering, University of Texas at Austin, 2002.