

Set-Based Prototyping with Digital Mock-Up Technologies

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Abstract

A prototype results from the need to verify various qualities of the product at different stages of its development. In set-based design, multiplying prototypes is particularly critical to enable a broad exploration of the design space before committing to a solution. The exploration targets the choice of the best of all viable concepts on one hand but on the other hand also focuses on documenting them to better orient the search during the next attempts. This ultimately contributes to gradually improving the company's engineering knowledge. According to current aerospace industry practices and considering the set based development paradigm in Lean thinking, an approach to handle multiple prototypes information with Digital Mock-Up (DMU) technologies is forwarded in this paper. This approach postulates that prototyping and testing activities may be supported by a Manufacturing Process Management (MPM) solution with a special use of three key functionalities, namely: Product Data Management (PDM) and MPM instantiation, MPM links, and Configuration Management (CM). These aspects are essential when handling multiple prototyping sets along with their test results.

Keywords: Prototyping, Testing, Digital Mock-Up, Product Data Management, Lean product development.

1. Introduction

Prototyping and testing work is usually done during product development for three main reasons: evaluate and validate design choices, mitigate uncertainty through real life assessment and learn by experimentation (Michaelraj, 2009). In the aerospace industry, evaluating and validating choices generally aims at demonstrating performance and compliance with design objectives and regulatory authority. Mitigating uncertainty consists of bringing several bodies of knowledge

into interaction so each one's influence is disclosed and taken into account as soon as possible. Based on advances in Digital Mock-Up (DMU) technologies and in simulation tools, real life assessment in modern engineering is now possible in both physical and digital worlds. As such, the cross-functional interaction spreads from digital modelling and simulation to physical construction and testing, as long as a physical test is necessary to explore a phenomenon that is not otherwise possible with a proven simulation-based experiment. Learning by experimentation, on the short term, supports design convergence. On the long term, it spearheads the core organizational learning system at the root of set-based design methodologies, witnessed for example in the Toyota Product Development System (Ward, 2007).

According to the specific processes and the amount and nature of information that can be generated, some specialized tools exist to support prototyping and testing during the aerospace product development. However, these tools retrieve engineering product information from dedicated systems in a transactional mode and are therefore rarely part of an integrated value stream or feedback iteration (Toche et al., 2010). The result is a situation where the development and test information system supports the construction and test of multiple prototypes but all relevant information pertaining to them remain scattered, reducing upstream and downstream visibility.

The work presented in this paper focuses on proposing a strategy to handle multiple digital prototypes (alternatives) in the form of DMU subsets that also enables synchronization with physical prototyping and testing information. The remainder of the paper is structured as follow: First, in Section 2, the switch from simulation to physical test is discussed and the necessity to combine their use and therefore to carefully handle the different prototypes is highlighted. Then, in Section 3, The intents in multiplying prototypes are presented in a lean approach to product development (Ward, 2007). In Section 4, the strategy to handle prototypes information in the context of a Product Lifecycle Management (PLM) infrastructure is demonstrated. Finally, in Section 5, conclusions are formulated and potential future research is articulated.

2. Combining simulation and physical testing

The last three decades have seen a rapid evolution in simulation tools and digital product development. Fig. 2.1 illustrates the contrast between the build-test-fix approach and the ability through the use of a computer to design, manufacture, test, and even service products virtually before manufacturing and tooling construction really starts.

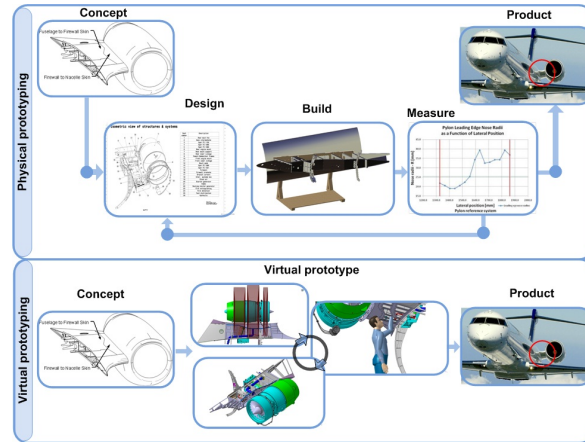


Fig. 2.1 Moving from physical to virtual prototyping

Geometrical representations through Computer-Aided Design (CAD) modelling are the norm nowadays and they form the visible part of the virtual prototype. The DMU gives an insight into the form and fit of assemblies of 3D solid models constituting the product. This functional virtual prototyping can lay down the operating function of the assembled product and be used in a virtual factory simulation (Lazzari et al., 2001; Ryan, 1999). Lazzari et al. (2001) and Ryan (1999) argue that the combination of the DMU, the functional virtual prototyping and the virtual factory simulation provides means to move from hardware prototyping practices to software prototyping and therefore eliminates the need for expensive prototypes that have to be built to verify the product functions and behaviour. However, some crucial limitations in functional virtual prototyping capabilities are still present today. The lack of technology to accurately represent the components' behaviour and their cross functional relationships under different conditions, the indispensable role of hardware prototypes in manufacturing organization usages, and the roadblocks to acceptance of process change are some of the core stumbling block to total virtual prototyping solutions. Therefore, the aim of enhancing the use of virtual environments during the development should entail a synergetic use of both physical and digital representations rather than the radical elimination of physical prototypes. In fact, with the advent of rapid prototyping technologies, hardware testing is done with more confidence and can sometimes truly be executed more quickly, at a lower cost and for tangible outcomes and rapid feedback that promote learning (Carleton et al., 2009). Van Der Auweraer et al. (2005) strengthen the view of mixing physical tests and simulations by indicating that physical test methods should be used to tune and validate simulation tools and thereby extend the applicability of these last ones. Fig. 2.2 illustrates the impact of noise and vibration evaluation in the automotive industry. It shows how combining physical tests and simulations delivers innovation (Van Der Auweraer et al., 2005). The Y-axis represents the technical capability for some engineering

tasks, specifically system verification, and the X-axis represents the overall effort needed to accomplish the tasks.

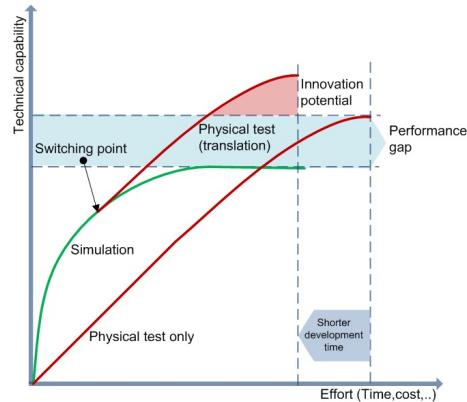


Fig. 2.2 Combining physical test and simulation to deliver innovation (Van Der Auweraer et al., 2005)

With simulations only, the available technical capability can be used very fast and the development time is then shortened. With physical tests solely, much more effort is needed to use the greater available engineering potential at its maximum, but uncertainties are firmly eliminated at each attempt. Switching from simulations to physical tests by exploiting the simulation's static results considerably reduces the effort to benefit from the overall technical capability. It also opens new fields for the validation and exploration of the product behaviour and therefore for innovation. Hence, any novelty either in physical test or simulation increases the engineering capability, extends the exploration potential and consequently exposes latent possibilities in product innovation. The optimal combination of simulation and physical test not only provides better system performance exploration, refinement and certification but continually reduces development time, strengthens virtual prototyping, and finally opens new solution spaces (Van Der Auweraer et al., 2005).

However, the simulation-to-test switching point is difficult to determine in practice because the current virtual product representations mainly deal with geometry and materials and they are strongly oriented towards manufacturing the product rather than the way it behaves in its physical environment. This is typically due to the lack of behavioral oriented descriptions of components to assess system's functions under diverse circumstances, even when considering the advances made with Multidisciplinary Design Optimization (MDO) methods (Panchenko et al., 2002). The correlation between design activities and virtual and real system testing has not yet been established and the implications of the testing results on the corresponding Computer-Aided Engineering (CAE) simulation models have rarely been addressed up to now (Riel et al., 2004). It is therefore necessary, as a first step, to provide means of linking these specific types of

information and transactions within the existing product development systems. In addition, any attempt in doing so should stem from current industry practices and paradigms and internal information technology infrastructures. Only by then will the combination of physical test and simulation generate full benefits.

3. Multiplying prototypes in a set-based approach to design

The power of physical prototypes in mitigating uncertainty and consistently driving innovation through design space exploration has been exposed above. This section discusses the reasons behind the existence and, especially, the multiplicity of prototypes in a set-based approach to the design of complex products.

3.1 About set-based concurrent engineering

Many approaches to engineering design are focussed on reducing cycle time following the famous motto “do it right the first time”. In terms of design strategy this has often been translated into a need to propose the right solution as fast as possible. As observed by Sobek II and Ward (1996), when dealing with the development of complex products, many US companies force the engineering teams to propose a feasible concept quickly so that it can then be optimized through numerous iteration loops. This pattern is understood as point-based because it focuses on one solution at a time and progressively refines it until all the stakeholders are satisfied with the outcomes.

Another design strategy, the set-based approach, has been the subject of a number of publications over the past 20 years. It is one of the pillars of “lean thinking” applied to product development observed particularly in the automotive industry through companies such as Toyota, Honda, or Denso. Here, engineers may reason and communicate about acceptable range of parameter’s values instead of single best value at a time. Set-based design allows windows of possibilities to align gradually and therefore the best of all worlds to be projected. It is rather a convergence process than an evolution (Sobek II et al., 1996). Participants bring sets of possibilities to the table and juxtapose them to find intersection of feasibility rather than successively criticizing and modifying a single option (Liker et al., 1996). Such a strategy has already proven to be efficient in some simple problems like selecting a group meeting time. Participants may submit their preferences and then the meeting organizer finds the most convenient time in the intersection of all, i.e. set-based solving. In contrast, point-based solving may involve either: participants compromising a meeting time one after the other until a satisfactory time emerges, or participants having a meeting to decide the

meeting time, or finally, some powerful members forcing everyone to comply with a selected time.

3. 2 Prototyping activities in a set-based concurrent engineering context

Wheelwright and Clark (1992) represented the Set-Based Concurrent Engineering (SBCE) convergence process with the *development funnel*, where a respectable amount of alternatives are put into several Design-Build-Test cycles. As time progresses, quantitative and qualitative data are gathered through simulation and test. Inferior alternatives are screened and only the most promising move forward into the funnel, until the best is produced and shipped to the customer (Wheelwright et al., 1992).

Denso, a first-tier supplier of Toyota, has brought such a process to finely tuned art and makes set-based design a gage of perpetual business superiority as witnessed by Ward et al. (1995). Only one year after establishing general design targets, Denso's engineers have already created full or partial prototypes evaluating their ideas as much as they can. By combining ideas and leveraging trade-off charts, graphs and past test data, Denso's engineers experiment extensively. They funnel their effort and after four years of development they are handling about three different designs with five prototypes each. At the end of the fifth year, they may submit two of them to Toyota for series production while being strongly confident in one superior design. At the same time, Denso furthers all its most promising alternatives into product families producible on the same lines. The approach is called *standardized variety* (Ward et al., 1995) and it gives Denso both the agility and capability to face current and future market trends. By multiplying prototypes, set-based design practitioners extensively explore opportunities and consistently generate knowledge to converge to superior designs or at least, optimal ones.

Finally, although the literature covers in great detail the use of sets in the conceptual and preliminary design phases (Sobek II et al., 1999), it remains unclear how these sets of information are formatted, classified, retrieved, dispatched, compared, and archived during a lean product development effort (Baines et al., 2006). It is argued that the power of SBCE has nothing to do with new computer tools (Sobek II et al., 1999) but it is however vital to clarify, or foresee, how such a strategy may be supported within the current product development information systems.

4. Handling prototyping information

Dolezal defines the DMU as *a digital 3D representation of a product together with its product structures and attributes* (Dolezal, 2008), all nested within a PDM system. Figure 4.1 illustrates this view.

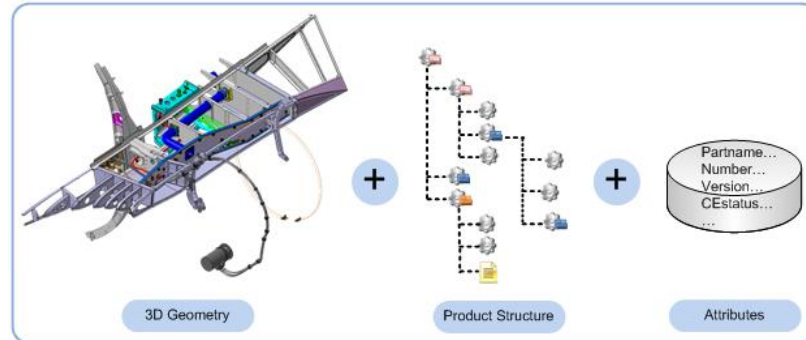


Fig.4.1 Digital Mock-Up components of an aft fuselage pylon

This section covers the current practices in using DMU technologies within the aerospace industry. It furthermore stresses the configured DMU concept to elaborate on the approach to represent and manage prototyping information.

4.1 Typical context of DMU technologies

As basic specification data, 3D geometry provides an insight into components shape, functions, and furthermore into design intents; They are the digital replicas of the parts to be produced. Attributes include all the metadata and lifecycle data for effective information management and distribution. Not restricted to information identification, attributes are key enablers for traceability and concurrent work. A Bill Of Material (BOM) represents a particular way of aggregating and presenting product data by disclosing hierarchical and logical dependencies among parts and all relevant attached objects. *As-designed* structure or engineering BOM (eBOM) and *as-planned* structure or manufacturing BOM (mBOM) are two frequently encountered BOMs. Some modern PLM frameworks already operate the interconnection between the two structures to support product definition and process planning concurrent activities (Fortin et al., 2007). This is typically done through robustly linked PDM and MPM modules. Fortin and Huet (2007) approach product development from a systematic perspective and address concerns on how to carry out the process in the current information-scattered environment that characterises the modern enterprise. The authors argue that the use of complementary information structures and an optimal parallelization of the

processes can significantly improve the product development performance through the digital collaborative environment.

Other arrangements or structures may exist to suit some specific lifecycle activities (Huet et al., 2011). For instance, prototyping and testing activities end up with *as-built* structures that identify and mirror physically assembled and tested prototypes. Some additional test rig components and relevant instrumentation to assess the prototype's performances may be included. The manufacturing strategy of the prototype and the specific test procedure both fashion the *as-built* structure. The same patterns to devise the component's mBOM are often followed to generate these *as-built* structures since both rely on approximately the same resources for the physical construction. However, hardware testing transactions and prototype information tracking are not addressed within common PLM visions (Toche et al., 2010).

4.2 An approach to represent and manage prototyping information

From the previous context and observations, it is hypothesized that prototyping and testing activities may be carried out following the MPM example (Fortin and Huet, 2007) with a variation on some key functionalities:

- PDM and MPM instantiation to trace assembled and tested physical prototypes. PDM and MPM instantiation consists in materializing a part or component by identifying and tracking the physical object with a digital one. This is done by assigning the unique supplier or shop-floor serial/lot number to the digital object which is then called *instance*.
- MPM links (Huet et al., 2011) to synchronize *as-built* structures with evolving *as-designed* alternatives. These complementary information structures links are not detailed here but it is assumed that *as-built* structures deployed within the MPM module remain connected to *as-designed* one through them.
- CM to handle multiple alternatives in parallel representing sets as well as physical yields. Figure 4.2 illustrates how CM is used to capture configurations (alternatives) from an evolving baseline structure and how combined with instantiation it generates frozen BOMs representing physically assembled and tested prototypes.

It should be noted that sets are introduced following a baseline structure because capabilities in platform design and modularity are acknowledged to intrinsically facilitate SBCE (Schafer et al., 2010). Indeed, modularity in product architecture makes it practicable to switch between design alternatives. To seek clarity, Figure 4.2 features a simplified example centered upon a conceptual item labelled A. This end item A includes two parts, C and D, and an assembly B composed of two parts B1 and B2.

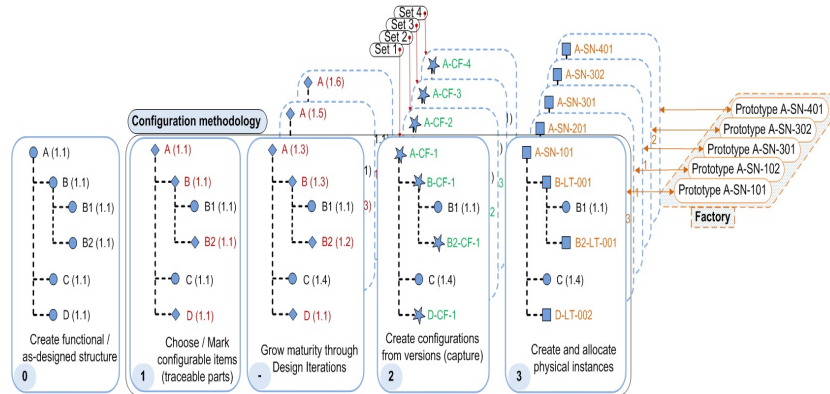


Fig.4.2 Configuration methodology to represent sets and physical prototypes

The baseline architecture as displayed in the first block of the diagram stems from the functional breakdown of the end item. The subsequent front blocks demonstrate the basic configuration methodology to represent a set and furthermore a physical prototype. The first step of the methodology consists in selecting and marking the relevant parts to be interchangeable and tracked throughout the lifecycle. These parts are designated as Configurable Items (CI) or traceable parts and the trace code can be a serial number, a lot number or a combination of both. The end item A, the sub-assembly B and the parts B2 and D are marked with diamonds from this step to identify them as CIs. Parts such as some fasteners, standard or obvious parts may not need strict traceability to lighten the process; this is why B1 and C remain untraced for example. As the design evolves, the components slowly mature and versions may change through iteration processes. Whenever a significant maturity is reached, or whenever a workable solution is settled, the corresponding combination is captured. This grossly means snap shooting versions of both the end item and its low level parts into a configuration which is adequately identified and saved for further retrieval. The design normally continues after such a capture, and some other satisfactory combinations may emerge; leading to new sets, new captures. As shown in Fig.4.2, configuration objects are marked with asterisks and they bear a similar suffix in their name to identify the actual set. At any time, the physical assessment of a set may be needed leading to the construction of one or several prototypes following the configuration. As such, the last front block in the diagram includes:

- Creating instances from configurations: an instance, which requires a serial number, is to correspond to an existing physical part, such as one manufactured for tests, at the appropriate level of maturity.
- Allocating instances: allocation is the process of associating specific end item instances and serialized parts to each other (PTC, 2008). In fact, a top-level end

item instance is not completely defined until all of the serialized parts and end item instances are associated with it.

The instantiation of an item is represented with a square in Fig.4.2. Fig.4.3 below exhibits an instance of the experimental forward engine mount of the aft fuselage aircraft pylon.

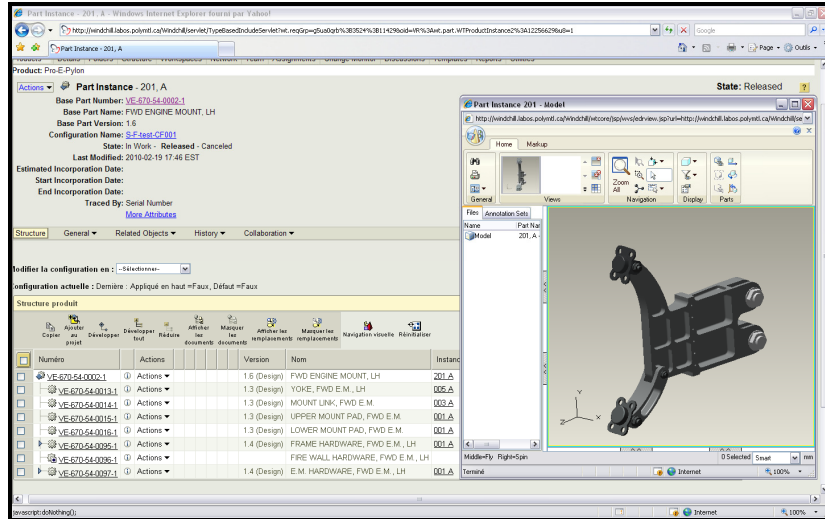


Fig.4.3 Instance 201 of the forward engine mount of an aircraft pylon– Courtesy of Parametric Technology Corporation

The physical instance of the forward engine mount is completely defined when all the traceable parts have been allocated. Of course this instance is related back to both its native CAD definition and the related CAE simulations.

As seen in the example, because the manufacturing serial numbers are identified, the physical parts are tracked and the physical prototype is uniquely mirrored. The methodology could also be applied when all parts and documents have reached the release status. This is to say, each tested, produced or delivered instance of the end-item is fully traceable with the preceding means.

5. Conclusion

The prototyping information management proposed in this paper allows the coexistence of multiple alternatives, the documentation of discrete sets and ultimately supports the funneling process core to Lean product development practices. The approach proposes to adapt the current use of PLM systems to

support SBCE. However, many other techniques constituting SBCE still need to be addressed, such as the intersection analyses between sets so critical to effective integration capabilities. Moreover, aerospace companies use several set-based practices but the unusual length of their aircraft development phase, the complex organization of their supply chain, and the difficulty to modularize aircraft functionalities remain major stumbling blocks towards proper SBCE implementation. Future research includes deploying a number of SBCE techniques in a scenario leveraging the approach presented in this paper. The aim is to devise a consistent methodology allowing lean product development to effectively happen in an aerospace context.

6. References

- Baines, T., Lightfoot, H., Williams, G. M., & Greenough, R. (2006). State-of-the-art in lean design engineering: A literature review on white collar lean. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 220(9), 1538-1547.
- Carleton, T., & Cockayne, W. (2009). *The power of prototypes in foresight engineering*. Paper presented at the Proceedings of the International Conference on Engineering Design, ICED'09, Stanford, CA, USA.
- Dolezal, W. R. (2008). *Success Factors for Digital Mock-ups (DMU) in complex Aerospace Product Development*. Technische Universität München, Genehmigten Dissertation, Munich, Germany.
- Fortin, C., & Huet, G. (2007). Manufacturing Process Management: iterative synchronisation of engineering data with manufacturing realities. *Int. J. Product Development*, 4(n° 3/4), 280-295.
- Huet, G., Fortin, C., McSorley, G., & Toche, B. (2011). *The management of manufacturing processes using complementary information structures*. Paper presented at the Proceedings of the International Conference on Engineering Design, ICED'11, Copenhagen, Denmark.
- Lazzari, D., & Raimondo, G. (2001). *Digital Mock-Up in support to Space Station elements Integration and Test*. Paper presented at the Proceedings of the 4th International Symposium on Environmental Testing for Space Programmes, Liege, Belgium.
- Liker, J. K., Sobek II, D. K., Ward, A. C., & Cristiano, J. J. (1996). Involving suppliers in product development in the United States and Japan: Evidence for set-based concurrent engineering. *IEEE Transactions on Engineering Management*, 43(2), 165-178.
- Michaelraj, A. (2009). *Taxonomy of Physical Prototypes: Structure and Validation*. Graduate School of Clemson University, Master Thesis, Clemson, SC, USA.
- Panchenko, Y., Moustapha, H., Mah, S., Patel, K., Dowhan, M. J., & Hall, D. (2002). *Preliminary multi-disciplinary optimization in turbomachinery design*. Paper presented at the RTO AVT Symposium on "Reduction of Military Vehicle Acquisition Time and Cost through Advanced Modelling and Virtual Simulation", Paris, France.
- PTC. (2008). Introduction to Windchill PDMLink 9.0/9.1 (Vol. T2136-090-02). Needham, MA, USA: Parametric Technology Corporation Global Services.

- Riel, A., & Brenner, E. (2004). *Simulation Interoperability in Product Development*. Paper presented at the Proceedings of the 2004 European Simulation Interoperability Workshop (EURO-SIW), Edinburgh, Scotland.
- Ryan, R. R. (1999). Digital Testing in the Context of Digital Engineering - Functional Virtual Prototyping, *VDI Berichte* (Vol. 1489). Berlin, Germany.
- Schafer, H., & Sorensen, D. J. (2010). Creating options while designing prototypes: Value management in the automobile industry. *Journal of Manufacturing Technology Management*, 21(6), 721-742.
- Sobek II, D. K., & Ward, A. C. (1996). *Principles from Toyota's Set-Based Concurrent Engineering Process*. Paper presented at the Proceedings of the 1996 ASME Design Engineering Technical Conferences and Computers in Engineering Conference, Irvine, USA.
- Sobek II, D. K., Ward, A. C., & Liker, J. K. (1999). Toyota's Principles of Set-Based Concurrent Engineering. *Sloan Management Review*, 40(2), 67-83.
- Toche, B., Huet, G., McSorley, G., & Fortin, C. (2010). *A Product Lifecycle Management Framework to Support the Exchange of Prototyping and Testing Information*. Paper presented at the Proceedings of the 2010 ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Montreal, Canada.
- Van Der Auweraer, H., & Leuridan, J. (2005). A new testing paradigm for today's product development process - Part 1. *Sound and Vibration*, 39(9), 14-18.
- Ward, A. C. (2007). *Lean product and process development*. Cambridge, Mass.: The Lean Enterprise Institute.
- Ward, A. C., Liker, J. K., Cristiano, J. J., & Sobek, D. K. (1995). The second Toyota paradox: How delaying decisions can make better cars faster. *Sloan Management Review*, 36(3), 43-61.
- Wheelwright, S. C., & Clark, K. B. (1992). *Revolutionizing product development: Quantum leaps in speed, efficiency, and quality*. New York, NY: The Free Press.

7. Disclaimer

Some commercial software systems are identified in this paper in order to facilitate understanding. Such identification does not imply that the software systems are necessarily the best available for the purpose.