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HOW RELEVANT IS DESIGN SCIENCE IN A GLOBAL PRODUCT DEVELOPMENT WORLD? – A REVIEW

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1 Introduction

Given the rate where high class academic papers are now being presented in Design journals and conferences, there is every hope that their relevance, in general, has a significant bearing on the needs and processes that industries in general wishes to adopt. In fact, this academic engineering design research should be assisting industries to innovate more creatively, create better and more competitive products more successfully, whilst achieving lower cost, higher quality products with shorter times to market – a tall order, but an ideal that academia should be striving to meet as the applied research sector matures.

This review focuses specifically on the implementation of Design Science research and asks if there is a continuous improvement of applicability to wealth generating capabilities of global manufacturing industries and to what extent is this improvement occurring?

The paper attempts to address the present day attitudes of Industry towards applying themselves to a) continuously reducing product time to market, b) getting the product more right first time and c) achieving the cost targets of the customer.

In comparison the review paper looks to assess what applied research papers are addressing in terms of identifying market needs, effective product development processes, new design tools/ techniques and design management issues.

This review focuses on a specific set of applied research topics and this has meant that the vast majority of references have been drawn from previous ICED conferences or Journal of Engineering Design papers.

2 The Industrial Imperatives

New product development is an absolute imperative for the survival and increasingly global competitiveness of manufacturing industries. Without a stream of regular new products or sound variants based on existing products, then the lifeblood of the company would be gradually strangled. Various reviews by Hart [1], Aroujo [2] and Fairlie-Clarke [3] on industrial new product development have recognised the importance of this to corporate and economic prosperity, coupled with the high risk of failure in such endeavours.

The scope of product development is normally recognised in industry as from the time the idea is generated until the product is launch in a production form on to the market. Whilst there are many models, the product development process itself within a manufacturing company has been recognised normally as wholly supported by such activities as marketing, sales, purchasing, distribution, etc. But this should be within a management framework that allows a manufacturing company to achieve a competitive profitable position in the market place [4].

In fact in the UK, most mainland European countries and the USA the more successful companies have adopted well defined and consistent product development processes in one form or another. However, many of the small/medium enterprises (SME's) are still "fire fighting" on a daily basis and struggling to put a consistent product development process in place whenever the OEM and first tier customer has not "imposed" their practices on the small company [4], [5].

Similarly, Arvidsson [5] has reviewed the practices of Swedish industry over recent years (using telephone interviews) in terms of their use and knowledge of robust design methodologies (RDM) rather than the adoption of product development processes. This RDM framework was primarily to design product insensitivities to variations in both product and process.

From some 87 Swedish manufacturing companies, only 28% showed familiarity with RDM and only 17% used robust design methodologies such as SPC, Design of Experiments, FMEA (product & process), DFM/A, Taguchi Methods, FTA, etc. Apparently the likes of Six Sigma programmes, QS 9000 certification (for the automotive industries), etc. have driven on the use of RDM. The 17% industrial users agreed that the use of RDM increased their competitiveness. Moreover, management commitment was seen as an essential pre-requisite for an extensive use of RDM.

Of specific importance to this review was that "many representatives in Swedish Industry agreed that they would increase their use of RDM if it had been integrated into their product development process". It was interesting but fascinating to note by Arvidsson [5] that this implied that a high percentage of the companies had a defined product development process and that integration of RDM in the process would probably increase the awareness and use of RDM.

Another common opinion stated in the Swedish industry survey was that the use of RDM would increase if it had been a customer requirement and that 67% of the Swedish respondents thought that RDM was useful. Inevitably this begs the question, not only on how customer requirements and regulatory bodies may be encouraged to be increasingly the key influencers, but also that of the seemingly relevant academic design researchers?

Haque [6] is of the opinion that Concurrent Engineering (CE) practices (also called integrated product development) were now practised widely in manufacturing industry to improve the integration and collaboration within the development process. This was by using a number of formal tools and organisational mechanisms to improve the quality, cost and delivery of a new product. Lean thinking on the other hand is a wider high-level philosophy focussed on waste elimination and flow of value, but does not provide the details needed to improve new product developments per se. I believe that neither in their own right provided the core activities synonymous with product development. However, they did achieve enhanced features that supported a more coherent global process.

Stauffer [7] provided a fascinating insight into the product development needs of smaller manufacturing firms in the USA that endorsed much of what had been reviewed above. Out of 61 individual smaller manufacturing companies (with 20-200 employees) from across 10 states, it was found that only between 40-50% of the companies considered that they executed product development activities better than their competitors. Clearly a lot depended on the quality of their competitors.

Overall the areas of greatest need were seen to be in the business related activities of product development. Improved marketing, project management and product refinements, as well as reducing the cost of product and processes were seen as the greatest need for improving competitiveness.

Stauffer [7] also identified that engineering design research should be increased in a) the connection between market, consumer and design information, b) support launching products

into the marketplace and c) equating product features with customer value to ensure a sustainable rate of return to small companies.
Eder [8] had previously established the fact that most engineering designers in Industry work within a relatively narrow set of design problems (a product family). Procedures and typical solutions were well known, even if they were not spelled out in detail. Only when an engineering designer meets a novel problem outside his/her immediate experience were any more formal procedures and methods needed.

3 The Academic Design Research Agenda

Given the extensive range of research papers on product development practices in industry, it was opportune to review where academic design research can or has had a bearing on industry. As stated by Blessing [9] Design is a complex activity, involving people, tools, processes, organisations and the micro and macro-economic environment (market, legislation, society) in which it takes place.
Design research aims at understanding design in all its facets that should lead to the validation of knowledge, methods and tools that improve the working practices in design.

Many strands of design research have emerged that are too diverse to include in this review. However, from this extensive range of possibilities I have attempted to focus this review into a limited number of major well defined areas of the product development process. These main "practical" strands of a) Creativity, b) Design Tools, c) Computer Aided Engineering (CAE) and d) Product Life-Cycle Management (PLM) have been chosen as I believe they have the greatest potential to impact on engineering industry practice with significant effect.

3.1 Creativity/Concept Generation

One of the aspects of engineering design that has been of particular interest to industry, but of less interest, seemingly to academic research to date, would appear to have been related to the process in concept design that has been called "product styling". Yet shape, surface finish, ergonomics and overall appearance play a critical role in the successful marketing and sales of a product.
Sauer, *et al* [10] have recognised the importance of product styling, because in order to increase the efficiency of the conceptual design phase, it was important to support the designer in structuring his problem solving process, particularly as the early design phase was especially essential for the success of a company. They have also analysed several development projects and developed a Pyramid Method that overcame some of the deficiencies of the phase orientated guideline VDI-2221.
Moreover, as Tovey [11] stated "decisions made at the concept and styling stage have a very significant influence on the subsequent engineering design activities". The form should be fixed as early as possible so that it can be translated into the hard data that informs downstream engineering processes.
In relation to the car industry, Tovey was clear that key parts of the stylists work had proved incompatible with computer-aided design (CAD) support; despite its advantages. He identified techniques that provided effective CAD support, without inhibiting the fluidity and richness of a sketch based approach. He proposed a hybrid technique that combined conventional sketches, sketch mapping, sketch modelling and non-contact scanning methods that apply to all product development processes-not just automobiles. Muller [12] also confirmed that many designers support themselves with classical handmade sketches before and also during the work with CAD. Using virtual technologies they have devised a first prototype of a digital sketching tool.
Given the fact from above that designers usually work best with sketches or rudimentary objects or models, Vidal *et al* [13] looked seriously at brainstorming as one of the most

widely used creative methods. From their studies they took one step further by using, in addition to oral expression, 3 variants - writing (sentential), drawings (visual) and objects (objectual) to generate ideas in a group brainstorming session. Their conclusions were particularly interesting as all the forms of expression were of benefit. However, the objectual variant of brainstorming was found to be the most effective of the 3 variants.

3.2 Design Tools

The range of practical and effective design tools has been quite extensive in academic research terms. From the Author's own UK research [4], it was probably the area of design research that has had the greatest impact on design practice in Industry over recent years. The range of tools extended from Design for "X", tolerancing, costing, assembly/disassembly, recycling, safety, Quality Function Deployment (QFD), TRIZ, etc.

QFD, Design for Manufacture & Assembly (DFMA), Failure Mode & Effect Analysis (FMEA), Fault Tree Analysis (FTA) and 6 SIGMA have been around the academic applied design research scene for a good number of years and some are continually being refined and implanted into industry practice. Rather than focus on these refinements to what are perceived as important but fairly traditional design tools, the Author has looked at other interesting papers that have been published and made considerable progress in somewhat different directions.

Tolerance analysis tools have increased their profile over the last few of years. In particular, emphasis has been placed by Lindkvist, Wandeback and Soderberg [14],[15],[16] on using as much process knowledge as possible in the early stages of product and production development. Lindkvist [14] highlighted a software tool methodology that made it possible to evaluate tolerance chain "stack-up" and supported the evaluation and early detection of geometry and tolerance problems during concept/detail design; thus minimising problems found later in production. Soderberg [16] provided an interesting application of the Lindkvist [13] software tool in terms of its application to seam variation analysis for automotive body panel design where flushness and gaps between panels took on increasing importance in any quality appearance evaluation.

Wandeback [15] added further design research knowledge that has practical importance to industry by stressing the importance for industry of learning to use measurement data as a source of information in their development process, thereby increasing confidence in the concept design.

Booker, Swift and Brown [17] have produced an excellent research paper that has reviewed extensively the current assembly-orientated design techniques available. These techniques have detected potential quality problems and identified the key issues related to assembly, quality, operations and the assembly technologies used. It brought out some startling facts in terms of the costs of controlling variability at the design stage, but equally as important, an assembly variability analysis proved to be useful in the identification of potential problems at the design stage. This has addressed a major industry requirement, crucial in the reduction of the quality related costs. Booker *et al* [17] are clearly of the opinion that industry still struggled to execute rigorous strategies for variation reduction. To meet this need, they concur with Wandback [14] that industry must adequately characterise their manufacturing and assembly processes through the introduction of process capability databases – using tools and methods for process characterisation.

In contrast, Ferrao, *et al* [18] have researched into the big issue of how recycling and end of life component processing should be addressed in its own right, rather than be implicit within the design practices of design for disassembly. It is the Author's belief that so much more design research activity should be developed on this topic in order to aid industry in establishing clear methods of introducing re-cyclability into its early design processes.

Whilst still in its formative stages, the research of Ferrao [18] established the foundations for a new DfR design methodology that incorporated environmental and economic information according to a set of specified parameters.

The integration of safety and risk into the product development process has been a growth area of design research and was well exemplified by P.J.Carkson [19], *et al* who reviewed the effectiveness of design in the UK health service. The objective was to reduce the risk of medical error and improved patient safety across the National Health Service (NHS). I would anticipate the outcome of the design review would also have a significant bearing on other global health services.

From the review the major conclusions were that a) the NHS was seriously out of step with modern thinking and practices with regard to design, b) there were no quick fixes, c) there was cause to question the design of medical devices, products, packaging and information and d) a lack of understanding of customer experience, human factors and user friendliness to the NHS brand.

In contrast Gauthier [20] had focussed on industrial accidents associated with industrial machinery. Despite FMEA, FTA, HAZOP and Risk Analysis tools being available in addition to European legislation on "Safety of Machinery" plus "Certificate of Conformity", this fresh piece of design research, whilst still not yet matured, has proposed relatively new concepts of formal risk analysis and control. These concepts should bring about a significant integration of global safety activities into the development process of machinery, rather than the sometimes informal present day approach of designers. Moreover, it built on the firm foundations of Wang [20] and Stoop [22] who have demonstrated that an efficient integration of safety during design is possible with very effective results.

The activities of Fargnoli and Pighini [23] have addressed safety at the concept design stage in the product development process in a somewhat different manner. They have brought in the effects of implementing safety on machinery costs. Using a Safety/Cost Ratio methodology (SCRM) they have identified for machinery design, that they were able to eliminate main risks whilst analysing the increased costs of implementing the safety features. In fact by choosing the correct safety devices using the SCRM, they found a considerable increase in safety with very little increase in costs. The SCR methodology appeared to have been positively useful and that it was being further validated with an extended range of machinery.

3.3 Computer Aided Engineering

These range of tools are very extensive and cover Computer Aided Design (CAD), Virtual Reality (VR), Computer Aided Analysis, etc. Again in the opinion of the Author, the purpose of the review was to explore the latest research activities that have the potential for a useful and immediate benefit on industrial product development practices.

The question was whether Virtual Reality (VR) was just a design tool that was just a passing phase in life and/or was only applicable to the large automotive companies? Or was it here to stay as an essential design tool?

Ottosson [24] had put a convincing case in his paper that some applications of VR have already matured, whilst others were still in their infancy. Of particular interest was the fact that in his opinion VR offered new possibilities in the field of product development by speeding up the pace and improving quality and usability; particularly in a distributed or global environment.

Of particular value from his "action research" was the fact that VR was a) useful for creating simulations, b) for the study of user behaviour, c) to train personnel skills and d) for broad-spectrum communication. In particular he emphasised that VR was a tool that enabled classical and dynamic product development by providing the means for sharing a vision of the product across a wide range of disciplines.

For example, aesthetic and ergonomic design was assisted by VR tools and would be invaluable in the communicating and selling of turnkey products-especially new products that were not yet in production. I would support the view of Ottosson [24] that whilst VR seemed to favour product development practices when many factors have to be taken into account, it would seem that the economic threshold and knowledge to implement VR was very high.

It would probably be applicable to the large global companies where product development continues around the globe over a 24 hour cycle. However, it is my opinion that there are VR technological developments that will allow SME's to use the benefits of VR in global product development over the next 5 years.

CAD/CAM systems become ever more comprehensive and easier to use by the designer and manufacturing engineer, that it would seem that there is little academic design research opportunity left in this context that could be relevant to industrial practice. Yet from recent publications in this area, this would appear not to be the case.

The design research of Szewczyk [25] has highlighted the real practical difficulties about the visual representations of interfaces within CAD that can affect users' abilities to comprehend the potential of their CAD tools. Misunderstanding the elements of the "graphic user interface" such as icons, toolbars, dialogues and cursors can somewhat surprisingly become a barrier to effective design work. Their research found that novices usually wanted to know all the tools and they actually tried to guess their meanings.

Whereas the advanced users have learnt to distinguish between important tools and the interface context, but they pay no attention to the context if it is not clear. They usually ignored many background tools and this has meant they did not expect to be fully comprehensible. As yet the research has led to some possible ways forward with this dilemma, but no definite conclusions have emerged as yet.

Boujut [26] has taken a slightly different human interface angle by questioning that CAD systems provide functionalities for sharing models and sometimes even annotations (attached text, images, etc). But these functionalities remain poorly employed. He argued that based on industrial experiences, providing annotation facilities within CAD systems was not enough.

Whilst no design tool have been developed from the research, the outcomes highlighted the human interactions to global design teams working on CAD systems and the importance of annotative processes when dealing with complex models that involved deeply interwoven process constraints.

At the other end of the CAD/CAM spectrum the complexities of blending complex surfaces and curve optimisation have been researched with practical benefits by Roy *et al* [27] and Prijic & Jennings [28]. Roy *et al* have identified in their research how time consuming and complex is the manual process of optimising curves and surfaces within a CAD system. They have then addressed the need to find a method to automate this optimisation process within the CAD/CAM environment with minimal intervention from the designer. This was primarily because the CAD/CAM environments used for surface modification provided only limited facilities for such an automatic process.

Whilst undoubtedly there are advanced CAD/CAM tools such as CATIA versions that have significantly improved on their optimisation capability, Roy [27] have provided a framework for surface optimisation within a CAD/CAM environment that did not require the Designer to have any prior knowledge about the internal representation used by CATIA. It has been found to be very convenient to use by the Designer on various industrial applications.

In a Similar manner Prijic & Jennings [28] have recognised that a significant amount of end-user time, cost and effort was expended by the designer in the creation of freeform sculptured surface blends in press and mould tooling. Consequently, they have identified an opportunity for utilising a programming and geometrical modelling design tool for the implementation of a free-form feature-based approach to freeform aesthetic design, using identified proprietary systems.

King *et al* [29] have taken a critical design research approach on how computer aided engineering (CAE) analysis tools have grown in their importance, particularly for reducing the level of hardware prototyping during product development and for improving understanding of the system under development.
Their research has been of real significance because it examined the implementation of CAE analysis tools in product developments over a variety of 5 different companies from different industry sectors.
With advanced CAE analysis tools in mind, such as CFD, FEA, multi-body systems dynamic modelling, etc., by correlating the results from the 5 companies, King [29] has established points of good global product development practice that integrated CAE analysis tools in a structured manner.

3.4 Product Life-Cycle Management (PLM)

The whole topic of PLM has been around for many years with the designer and the product development process teams. Yet generally with the exception of the global industries, most SME's have not addressed the subject too seriously throughout Europe. This could be because the cost of a complete suite of PLM software was prohibitive. Or else it had not been recognised that bespoke PLM software could be introduced on an incremental basis rather than *en block*.
Weber *et al* [30] in their excellent paper were of the opinion that the environment of today's Product Data Management/ Product Life-cycle Management (PDM/PLM) systems was characterised by the co-existence of various independent tools, each based on their own specific product model.
In this environment the PDM/PLM mainly focused on the administration of computer files generated by these tools without having much access to the actual content of the files. Consequently, such systems did not *know* anything about characteristics and properties of a product, let alone their inter-relationships. So they could not offer a continuous support to the whole product development process.
Whilst they do not as yet offer a robust researched solution, they have proposed the potential of a novel Product –Driven Development/Design (PDD) modelling approach that was of an advanced kind of PDM/PLM system. When introduced the approach should be able to formally distinguish between properties and characteristics and support the control and management of the design process itself in a critically important manner.
Moving on to a higher plain, Payne *et al* [31] looked at how significant changes within the aerospace industry were required for developing complex products in a globally distributed environment. The trend to globalise product development had increased, with incentives such as lower cost labour in developing countries and shorter development times. In addition, many organisations operated with only a core of full time permanent employees, outsourcing the skills required on a contract basis when specific jobs were required. The authors made the point that integrated product development (IPD) had been effective up to a point in implementing the key features of the design process, but only when individuals work was collated together. However, present practices do not easily manage product development in a geographically distributed environment.
Within this modern context, Payne *et al* have introduced and are working with industries on researching a new exciting approach known as the Macro Concept that has the potential of working in a distributed environment. It attempts to support the human elements and soft issues of the product development process. The two components of the Macro Concept are the Core Team and the Task Teams which did not depend on the need for collocated teams. The results of further outcomes from the research could have enormous benefits for the way global industries operate on developing new products.

Rouibah & Caskey [32] and Coates *et al* [33] have taken a different look at similar aspects within a PDM environment and addressed the coordination of design work within the concurrent engineering environment. Rouibah [32] recognised that managing information workflow processes were critical in order that product design in the distributed supply chain was accomplished in less time, with less effort and with superior results. Similarly Coates [33] reviewed and researched into what effective engineering management coordination requirements were necessary to the successful operation of organisations. There was presently in existence a broad and varied understanding to design coordination.

As a result Rouibah [32] presented in a fascinating manner the working concept of an EWF (Engineering Work Flow) method that was more of a generic than specific approach for good industrial practice. It linked product data and workflow management, whilst defining the control processes to coordinate co-operation and link the people involved to the activities and data in a CE environment.

In contrast Coates *et al* [33] produced a challenging more comprehensive people-centred approach to operational design coordination than currently existed. It emphasised in some detail that the key elements of operational design coordination was dependant on knowledge related to coherence, communication, task management, schedule management, resource management and real time support.

4 Conclusions

It would be impossible to review comprehensively the full extend of applied design research that is presently being addressed in academia over the past few years. The topics are far too extensive. So I have focussed specifically on a few areas of critical importance to industry such as Creativity, Design Tools, CAE and PLM.

From the Authors own research in the UK plus others identified in this review across mainland Europe and the USA, I have drawn the conclusion that a lot of "blue sky" intellectual design research continues to be prevalent across academia. However, whilst I have been highly critical in the past, there are now immensely encouraging signs that academic design research in specific applied research areas and specific University design departments were producing intellectually challenging outputs that were being adopted by industry with considerable delight and satisfaction.

Whilst it was difficult to quantify the extent of these improvements (a possible fundamental research topic in its own right), from the Author's experience of working with/assessing a considerable number of European and USA companies in recent years, the improvements on global product development would appear to have been very significant across many of the conventional engineering disciplines.

This review has given an insight into some of these important outputs and hopefully removed much of the doubt about the usefulness of academic applied design research to sound industrial practice in the 21st Century.

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