Title:
Research Methodology Framework for CAD/CAM-A Synthesis of Existing Approaches

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Introduction:
Recent comments from leading engineering design researchers [7] suggest that research methodology is not well considered by most engineering design researchers. Other researchers [5] have mentioned that compared to disciplines like social sciences, “scientific and engineering disciplines are far less methodologically aware”. Blessing and Charabarti [1] pointed out that there are fewer books and research publications addressing research methodology that is appropriate for design research. CAD/CAM research which can be considered as a sub-field of design research is even much less considered when it comes to existing research methodology. Eckert et al [4] discussed the issue of wrong usage of the existing frameworks such as Design Research Methodology, DRM [1] within the CAD/CAM or design research community. This wrong usage is indicated by a rigid adoption of research methodological frameworks and could lead to members of the research community questioning if research methodology serves any purpose.

The above reasons show that the existing research frameworks are not the problem, but that there is a need to raise awareness in the research community of the existence of appropriate research frameworks and the best way to use them. This paper is a contribution to raise awareness and demonstrate how we have tried to use these existing frameworks in our CAD/CAM research. This contribution is presented in three steps: (a) Presentation of data on how design researchers (this includes CAD/CAM researchers) use the existing research frameworks, (b) Identification of areas where we have needed clarifications on different terminologies and constructs used by different research frameworks and how we reconciled them (c) A synthesis of the examined research methodology frameworks that can inform our CAD/CAM research and (d) An example of how the synthesized research framework has been used.

It is to be noted that the synthesized framework is not the proposal of another design research framework expected to be used by other members of the research community. Rather, it is the documentation of our understanding with the hope that it could lead to “conversations” and that other documentation could be proposed by other members of the community (especially by leaders of research groups), pointing us to a shared understanding.

Existing Engineering design research frameworks and their synthesis:
Over the past 2 decades, several frameworks have been proposed for engineering design research. These include the following: (a) Blessing and Chakrabatti’s Design Research Methodology (DRM) [1], (b) Eckert et al [4], (c) Reich [8], (d) Cantamessa [2] and (e) Duffy and O’Donnel [3]. The citations of these research frameworks are shown in fig. 1. Obviously, the highest citation is for DRM and this is after it has been scaled down by 10 to avoid obscuring the citations of the other frameworks. While the number of citation for DRM is relatively high, that for others are really low. Even for DRM, when self-citations and casual

citations are considered, only a few researchers have actually used the framework, the number of those addressing CAD/CAM research being less than 10.

A surface observation of these research frameworks could indicate more differences than actually exists. However, when considered using methods for creating shared understanding such as ontologies, a convergence in the constructs and the relationship between those constructs emerges. The differences would be observed to arise from using different terminologies for the same or similar construct. Le Dain et al [6] has also reported that the classification of types of research studies reported by Cantemessa [2] can be mapped to those in DRM.

At a general level all the frameworks consist of 2 types of research outcomes. The first type of research outcome (referred to as Descriptive study) considers achieving an understanding of the design phenomenon (referred to later as Practice Environment, PE) being investigated. This type of understanding could be conceptual constructs, descriptive, explanatory or predictive. Examples in CAD/CAM research could be definitions or identification of concepts (e.g. what is a feature?), categories/classification (e.g. taxonomy of features), structural description (e.g. what type arrangement of geometric and topological entities would be required to describe a solid object with a desired richness in descriptive detail?). Explanatory-predictive outcomes could include outcomes such as identification of the reason for the observed characteristics of an optimization algorithm.

The second type of research outcome (referred to in this paper as a prescriptive solution) develops a solution for improving the performance of the investigated design phenomenon. Usually in CAD/CAM research this is usually trying to develop a computer-implementable tool to solve a particular problem in design. Ideally this should be based on the understanding developed in the descriptive research outcome. For example: Given the reason for the observed characteristics of an optimization method, how can the variables or constructs be re-designed so as to achieve better performance and so support a design improvement? Note that when the research outcomes are clearly stated as in examples above, they can be easily turned into research questions or aims and objectives that would produce good contributions to the body of knowledge in CAD/CAM.

The types of research outcomes as discussed above are informed by the vision/mission/purpose of the research programme being carried out. To have interesting results, the purpose here should approach answering fundamental questions of the field (e.g. fundamental reason why we need to use computers in design). Fundamental assumptions (often referred to as paradigmatic position) would affect the purpose of the research programme as well as other aspect of the research. Thus it is useful that guidelines to help uncover assumptions are available, so that they do not bias the results. For the research outcome to be practically useful, it needs to be informed by the practice environment. Finally, the type of research questions posed affect the type of research methods (RM) employed to create results which can be demonstrated to meet acceptable validity criteria.

Not all the constructs of a research framework described above are present to the same level of details in the 5 research frameworks considered. Table 1 presents a comparison of how the constructs are present or absent in the research frameworks earlier mentioned and indicates different terminologies used for them. Together with figure 2 these relationship between the different frameworks are illustrated. In fig. 1, the presence of a construct is indicated by “Y” (for Yes) or the alternative terminology it uses, an absence of a construct by “N” (for No) or uncertainty of how well the construct is addressed by “Y/N”. These indications are the interpretation of the author and needs clarification from those who have proposed these frameworks.

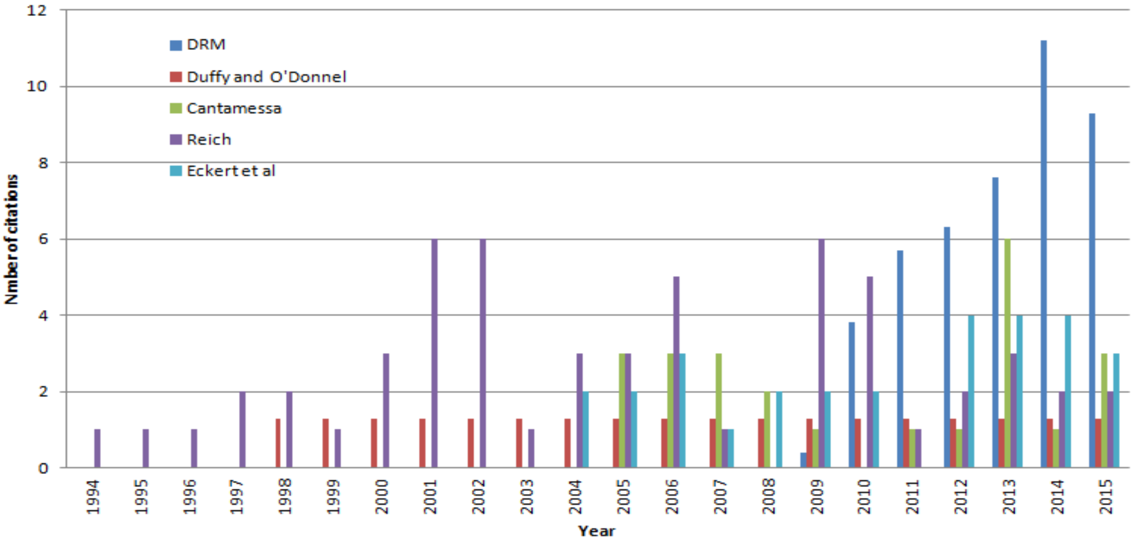

Fig. 1: Citations for existing design research frameworks.

Tab. 1: Comparison of Design Research Frameworks.

Constructs in framework		Design research frameworks			
		DRM	Duffy	Cantam	Eckert
Practice Environment, PE	Established Practice, EP	Y/N	Reality	Design	N
	Commercial Tool Development, CTD	Y/N	Y/N	CTD	N
	Technology Adoption, TA	Y/N	Envisaged reality	Y/N	N
Assumptions		Y/N	Y/N	N	N
VMP	Vision, Mission Purpose, VMP	N	Yes?	N	N
RQ	Research Questions	Y/N	Y/N	Y/N	Y/N
Research Outcomes	Understanding of Artificial Phenomenon, UAP	D	D	U of design	Empirical studies
	Descriptive (D) Understanding, DU	D	D	U of design	Empirical studies
	Prescriptive (P) Understanding, PU	N	N	N	Y/N
	Prescriptive Solution, PS	P	P	Dev of new tools	Development of tools
	Implementation of PS, IPS	Yes	Computer Model	I tools	Development of tools
	Lab Test of IPS, LT	Yes	Yes		Yes
	Field Test of IPS, FT		Yes	I tools	Introduction of tools
	Established TA	N	N	Yes	Y/N
RM	Research methods	Y	Y/N	Y/N	Y/N
Validation	Validation	Y	Y	Y/N	Y

While there are commonalities between all the research frameworks considered in this paper, there are also areas of distinctiveness. This distinctiveness of each framework is expected since each framework is ultimately grounded in the unique experience of those who developed it. It is not expected that the research community would reach a state of consensus where there is only one framework employed by all researchers. It is expected that as more research groups engage in the "conversations" of documenting their understanding of how to conduct CAD/CAM research, more commonality would emerge shared by the community. Distinctiveness in the framework is expected to lead to clusters of "schools of thought". The framework by Reich (not included in table) goes into more depth on the paradigmatic assumptions which should help the researcher identify the nature of the reality in the investigated phenomenon. For example, whether the phenomenon involves objective reality or it is a phenomenon with higher level of subjectivity such as the thinking process of a design practitioner which may be difficult to articulate, yet need computer support. As noticed from table 1, guidelines to help uncover assumptions is perhaps the most important areas that all framework need to address more The framework by Duffy has a distinctive aspect in being the only one with consideration of the vision, mission and purpose of the research programme, though clarification is needed on the degree to which the purposes addressed fundamental questions. The paper also shows how the theories that are grounded in axioms can be formulated.

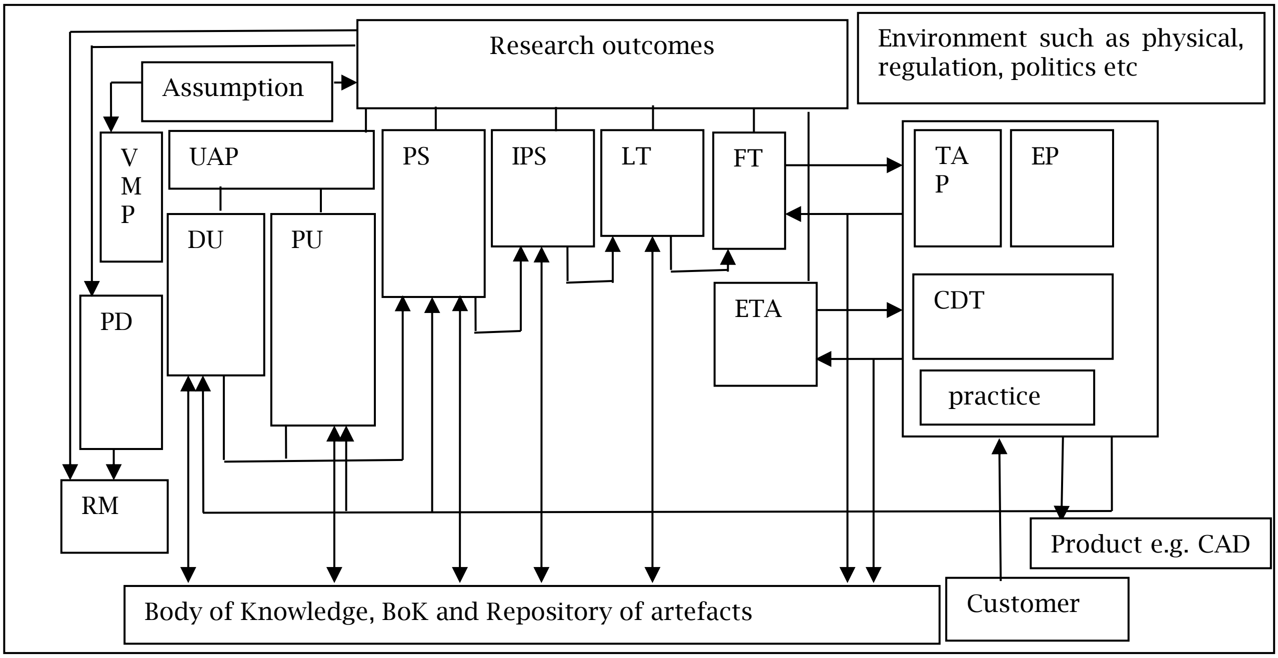

Fig. 2: A synthesis of the existing design research frameworks.

<u>Application of synthesized research framework to optimization of sustainable machining:</u>
The application selected could be considered in the general area of engineering optimization as applied in CAD/CAM area like CAPP. But it also requires using a lot of science type laboratory study used in most engineering research following the experimental methods of the sciences. There are aspects that interfaces with decision making which fall outside conventional engineering research. The case is retrospectively interpreted to show how the application of a design research methodology could have improved the research process.

The practice environment is the machine shop of manufacturing enterprises. The research did not start with specific problems from real manufacturing environment. Rather it was expecting to solve a general optimization problem that is hoped can work within existing commercial Computer Aided Manufacturing (CAM) software. Retrospectively, it is felt that this is too artificial a problem and would not address the Theory-Practice Problem as explained in the works of Reich [8]. To address these shortcomings, observations were conducted in 4 SMEs and over 40 practitioners were interviewed.

These process together with literature review of the Body of Knowledge (BoK), clarified that the type of research outcome required an understanding of the machining process (i.e. descriptive model) which confirms the degree to which reports in the literature indicating that reduction in energy consumption takes place at higher process parameters is true. The second research outcome was to propose a prescriptive solution to improve the phenomenon by determination of process parameters which results in reduction in energy consumption. The 3rd research outcome was to implement the prescriptive solution (i.e. IPS) in a form that practitioners would be able to use, then carry out lab test (LT) as well as field test (FT). With these clear outcomes, well posed research questions could be posed. For example, for outcome 1 the research question was: How does increase in process parameters affect energy consumption and how does this compare with results reported by other researchers? This a research question for a confimatory descriptive-explanatory research outcome.

Research methods (RM) corresponding to the research questions posed were formulated. Mathematical models of the machining phenomenon were created and validated with experiments leading to the descriptive model with predictive capability as shown in fig 3 for Specific Energy consumption SPE at different material removal rate, MRR. Also optimization algorithms were investigated to determine the best fit for the phenomenon. Laboratory-based test showed that improvements up to 60% reduction in energy consumption could be obtained. However, the field test ran into challenges and was only able to raise the awareness of the practitioners of the possibility of energy reduction that can be achieved. The reason for this failure is now realized (using the synthesised framework presented in the previous section and fig. 1) to be due to low contextualization of the problem in a real practice environment.

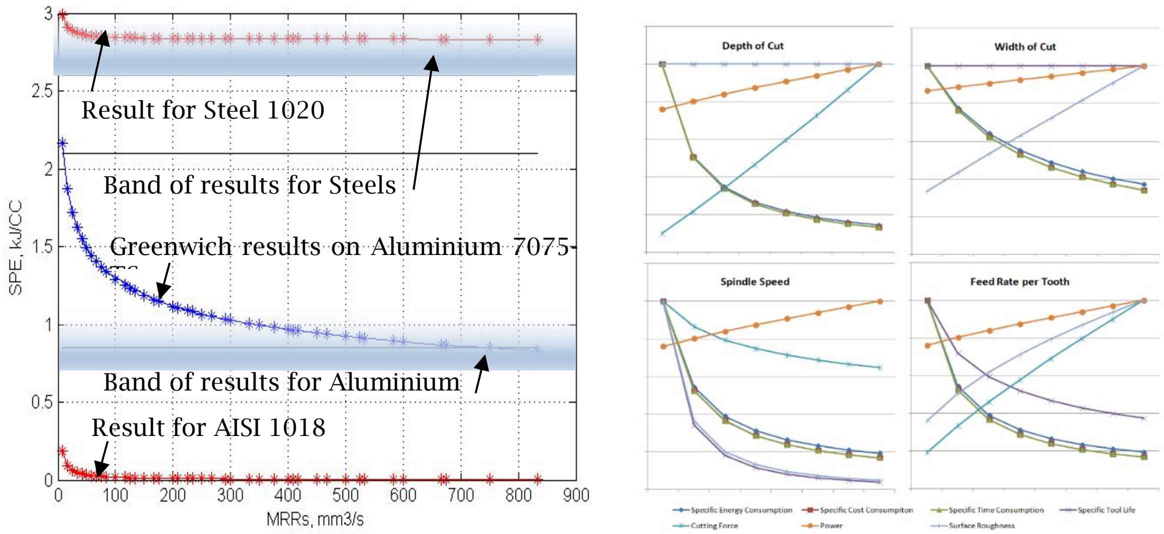

Fig. 3: Predictive model for energy consumption at different process parameters.

Conclusions:

In investigating the existing research methodology applicable to CAD/CAM research, the following conclusions have been reached:

- The usage of the existing research methodology frameworks by CAD/CAM or design researchers is still low.
- DRM forms a large portion of citations, perhaps because it has been articulated in some depth into a book. Other frameworks that complement the DRM perspective need to be articulated in similar depth.
- It has been demonstrated that by clarifying terminologies used in the different research methodology frameworks, it is possible to arrange them into a coherent framework that enables a shared understanding offering the strength of each framework.
- The application of the coherent framework to a case indicates that better research workflow can be achieved without stifling the researcher's initiative.
- More in-depth empirical research on the usage of research methodology frameworks by the research community is required.
- The synthesized framework needs to be extensively tested for correctness of representation by getting feedback from those who proposed the framework considered.

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