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Digital Modelling Methodology For Effective Cost Assessment

K. Agyapong-Kodua*, K.B Asare, D. J. Ceglarek

WMG, University of Warwick, Coventry, CV4 7AL

* Corresponding author. Tel.: +44 24 765742; fax: +0-000-000-0000. *E-mail address:* k.agyapong-kodua@warwick.ac.uk

Abstract

Research advances in digital factory design has led to a number of simulation techniques and tools which have the capability to represent aspects of the lifecycle of manufacturing systems. Although this is the case, analysis of key performance indicators (such as cost) are not very advanced when compared with other digital manufacturing simulation applications. To address this gap, this paper proposes a dynamic cost modelling (Product, Process, Resource, Cost-PPRC) methodology which is based on an initial digital modelling of the (perceived or real) production system and then associating product features with the capabilities of the production system. The paper reports a case application of the PPRC methodology for remote laser welding (RLW) of a car door. The methodology provides a basis for economic justification of product, process and resource related changes.

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1. Introduction

The drive for competition and business sustenance over a production systems' life time requires that manufacturing systems are designed to produce cost effective and quality products [1-3]. Since most decisions which are cost sensitive are taken at early stages of the design phase, it is necessary to support designers to understand the cost implication of their engineering decisions [4]. Achieving this is not trivial, because there are a number of competitive key performance indicators that designers will have to control to reach optimal design solutions [5]. To manage this challenge, proponents of cost engineering and accounting [2, 3, 6, 7] have recommended a number of approaches for cost estimation of projects, lifecycle analysis, technology down selection and assessment of economic viability of engineering projects. A review of these bodies of literature however shows that due to the inherent complexities and dynamic changes in product, process and resource requirements, it is fairly difficult to estimate, predict, control and monitor cost consumption appropriately. It was also noted that traditional cost accounting practices are best deployed to manage and control cost during operational stages of manufacturing systems but less helpful during early stages of product, process or resource systems design. Coupled with this, traditional cost accounting practices have not kept up with the advances in design and manufacturing technologies [4]. Current cost accounting techniques may be able to provide 'static cost' impressions when fed with suitable information but limited in predicting cost as a result of frequent engineering changes of dimensions, materials, tolerances, shapes and so forth.

To help overcome this, a novel dynamic cost modelling methodology (product-process-resource-cost-PPRC) is introduced. The science behind this methodology is that, product features can be associated with 'process capabilities' which can also be associated with 'resource competencies and capacities'. Cost is therefore generated through the consumption of 'resources' in the realisation of 'processes'. As a result, changes to products, processes and resource designs and their utilisation have significant causal impact on cost. The PPRC modelling methodology is commutative and derived through a conceptual knowledge model using semantic technologies. The initial application (which is reported here) of

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the PPRC methodology was realised in a case modelling of a novel remote laser welding (RLW) of a front car door.

It is important to note that the focus of this paper is on the methodology and not the detailed PPRC tool development hence the detailed databases, ontology creation, semantic modelling and reasoning are not presented in this paper.

2. Review of digital cost modelling techniques in support of engineering changes

Literature shows that estimation of product, process and resource cost has been mainly achieved through traditional cost accounting methods [8, 9]. Despite their long industrial adoption, traditional cost accounting models are usually intended for management and financial appraisal and do not necessarily reflect the cost implication of engineering decisions [10, 11]. Consequently, current generation independent cost accounting models perform less well when applied to dynamic product and process design scenarios.

An earlier study on digital cost modelling by Boehm [12] revealed 7 techniques with capability to support early stage engineering design analysis. These techniques were noted as: Parametric, Expert judgment, Analogy, Parkinson, Price to Win, Top down and Bottom-up. A careful study of these techniques however does not show how product changes are reflected in cost models and thus provides limited mechanisms for reflecting engineering changes. Being able to reflect the cost implication of engineering changes during new product developments is however crucial. Several other authors [2, 9, 13, 14] have provide alternative cost modelling classifications with the view to document practices which are common in industry and academia. They reported intuitive, parametric, variant-based, statistical, analogous, generative, analytical and feature-based methods. But more critically, there was no connectivity between the techniques and the scenarios under which they could be applied. This leaves the reader with vast number of techniques without explicit application scenarios. Also despite the different techniques reported, there was limited knowledge on how the integrated strength based on the unified application of a set of cost modelling techniques can be harnessed. Initial attempts to place a structure around cost modelling techniques was proposed by Agyapong-Kodua [15]. The author proposed the use of system dynamic causal loops to outlay modelling needs and then based on cost modelling requirements; map the individual strength of the techniques unto the modelling requirements. Although this approach seems worthwhile, Ajaefobi [16] has reported that no single solution is often the panacea for success in cost modelling and therefore there is the need for synergistic application of various techniques towards cost modelling. Further research [3, 7] has shown that well described statistical models can help identify causalities and correlate cost and product characteristics to obtain a parametric function with one or more variables. This seems worthwhile and can help formulate the correlation between product, process and resource variables.

Despite the success reported for some of the existing digital cost modelling techniques, Collopy and Curran [17] reported that there is generally, cost modelling challenges associated with: complexity of the cost; cost model validation; presence of cost drivers outside designs and non-objectivity of estimates in some cases. Other supportive work to associate cost information with product design for use in the aerospace industry was provided by Tammineni [18]. The research led to the development of a tool which is able to provide incremental cost fluctuations in response to changes in component geometry. This research achieved very useful outcomes but limited to the aerospace industry and also users have limited chance in interrogating the manufacturing systems model which is behind the cost engine. This therefore makes it difficult to be applied in other engineering business domains. A similar knowledge based model for modelling the cost of designing composite wing structures in aircrafts was provided by Verhagen [19]. Jin [20] provided a very useful integration method for automated recurring cost prediction by employing digital manufacturing technology. The study developed a prototype tool for integrating assembly time cost and parts manufacturing costs, however the authors focussed on manufacturing cost rather than estimating the total cost to include investment, overheads, etc.

3. Literature analysis and requirements specification for PPRC digital cost modelling methodology

From the above literature review and based on the authors' experience, it can be deduced that:

- Major design and engineering decisions bother on cost but usually designers concentrate on the technical feasibility of their technologies with little consideration of the cost implication of their decisions. In practice, costing is usually considered at the later stage of the design process. Currently, major cost estimates are done after design decisions have already been made;
- Accounting data are most often subject to financial report needs and not necessarily tailored to suit first class design engineering activities;
- Current best cost engineering tools do not necessarily recognize actual load conditions of production facilities and therefore cost information may represent nominal conditions of the manufacturing system's operations;
- Manufacturing, design and cost knowledge are mostly isolated although required to complement each other. The implication of such separation can be time consuming and expensive as it may require several levels of iteration to reach optimal decisions.
- Complex design and manufacturing technologies have emerged and there are limited equivalent digital cost modelling tools and techniques to support advanced engineering solutions derived through these applications.

Based on these observed gaps in existing cost modelling techniques in support of engineering changes, there is therefore the need to:

- Develop a robust dynamic cost modelling methodology which integrates product, process, resource and cost (PPRC) knowledge so that the cost implication of changes to any of the PPRC components can be reflected simultaneously;

- Create a PPRC model which is able to reflect real-time production situations and their possible change scenarios. The model should be flexibly dynamic such that changes can be updated easily. This must provide customised reflection of company-owned manufacturing resources and their accounting data;
- Develop a methodology which suitably extends current advanced product, process and resource (PPR) modelling techniques and tools; and enable traceability of costs to specific products, processes and resources.

4. The PPRC modelling methodology

The fundamental assumption behind the PPRC modelling methodology is that, all products (including components) require processes (and their sub-activities) to realise them. Processes (and activities) on the other hand are realised by resources (machines, people, software/technology and other fixed assets). It is the utilisation of these resources which generate cost.

The PPRC methodology (see figure 1) therefore begins with the creation of process models which represent possible operational sequences capable of meeting the requirements of the product model (usually represented as a CAD model). For familiar products, the creation of these sequences of operations may be simple. However, for new products, several iterations may be required and assessed before suitable process sets are identified. While doing this, product features are carefully documented and mapped unto the process types in a database. For existing production systems, an independent resource model representing the production capacities and competencies are then created. However, for new products, resources capable of meeting the process requirements would have to be modelled. This leads to a model of process capabilities and resource competences. The association of processes with resources although dynamic, can be flexibly adapted to meet individual production systems' needs. This requires thorough verification with domain knowledge holders to ensure that process and resource associations are correct. A similar logic is used to build cost databases which are essentially based on the degree of resource consumption. The development of the process and product models is commutative hence depending on the scenario, one could come before the other without creating any technical difficulty. As shown in figure 1, most engineering activities (e.g. Finite Element Analysis, FEA; Computational Fluid Dynamics, CFD; etc.) result in changes to the final product features. This is the reason why in the PPRC methodology process definitions are linked to the product features instead of the individual engineering activities. Product features therefore become the major geometric cost drivers. For example, for assembly processes, number of components, weld, weld length, weld type, weld production method are typical examples of cost drivers.

The flexibility of the methodology is such that the manufacturing system model can be derived and integrated also from state of the art factory design tools such as DELMIA, Technomatrix PLM, FactoryCAD and so forth. Databases from these tools can be extracted and linked together in the cost modelling workbench 9in this case the aPriori tool was used). The novelty of the methodology rests on the ability to link product features with manufacturing system capabilities and competencies as well as cost databases so that engineering changes can directly be reflected economically.

The procedure for the development of the overall PPRC tool (only the methodology and application is reported in this paper) is as follows:

Step 1: Derivation of a virtual process-resource-cost systems model

This may represent a specific internal plant or a broader network of organizations (plants). This model rests on a semantic reasoning engine which supports a number of integrated processes, resources and cost databases.

Step 2: Product feature correlation rules

Product features are correlated with process, resource and cost data with the ObjectLogic ontology language within the 'OntoBroker Reasoner'.

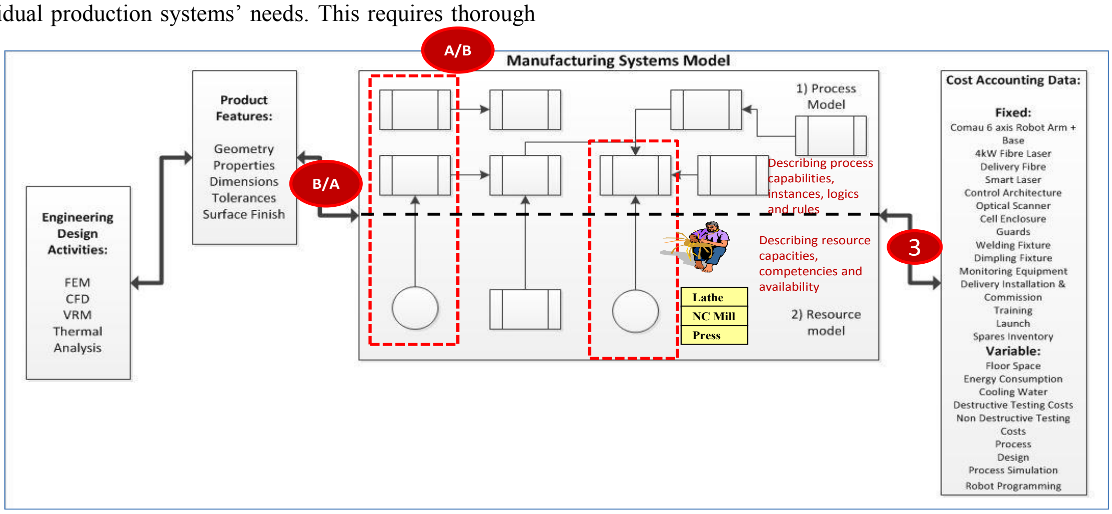

Fig. 1. Methodology for PPRC modelling

Step 3: GUI development

Steps 1 and 2 generate the backbone technology. In the third phase, the backbone is connected to a suitable GUI technology for user interaction.

Step 4: CAD model importation

With the preliminary developments completed, CAD models can be imported into the cost modeller for cost assessment.

5. Case application of the PPRC methodology

An excerpt of the case study related to the cost modelling of the production of an inner car door with the remote laser welding (RLW) technology is presented. The RLW technology is a novel joining technology with reported benefits such as reduced processing time of 50-75%; decreased factory-floor footprint of 50%; and reduced environmental impact by 60%; when compared with its competitive technology, resistance spot welding (RSW) in automobile sheet metal assembly. RLW has potential to promote competition and lead in eco-welding technologies.

Step 1: Creation of the virtual PRC systems: Three initial process maps representing possible ways of lab-prototyping car doors through the RLW technology were developed. Figure 2 shows an example process map developed with modelling constructs of the Open Systems Architecture for Computer Integrated Manufacture (CIMOSA). The three process models were evaluated for feasibility, timeliness and flow logic. The three sequences were further developed as PERT models describing the flow of materials, equipment and human resources in a digital modeller, DELMIA. This aspect is not included in this paper. As a result alternative process networks were simulated and the most optimal process selected.

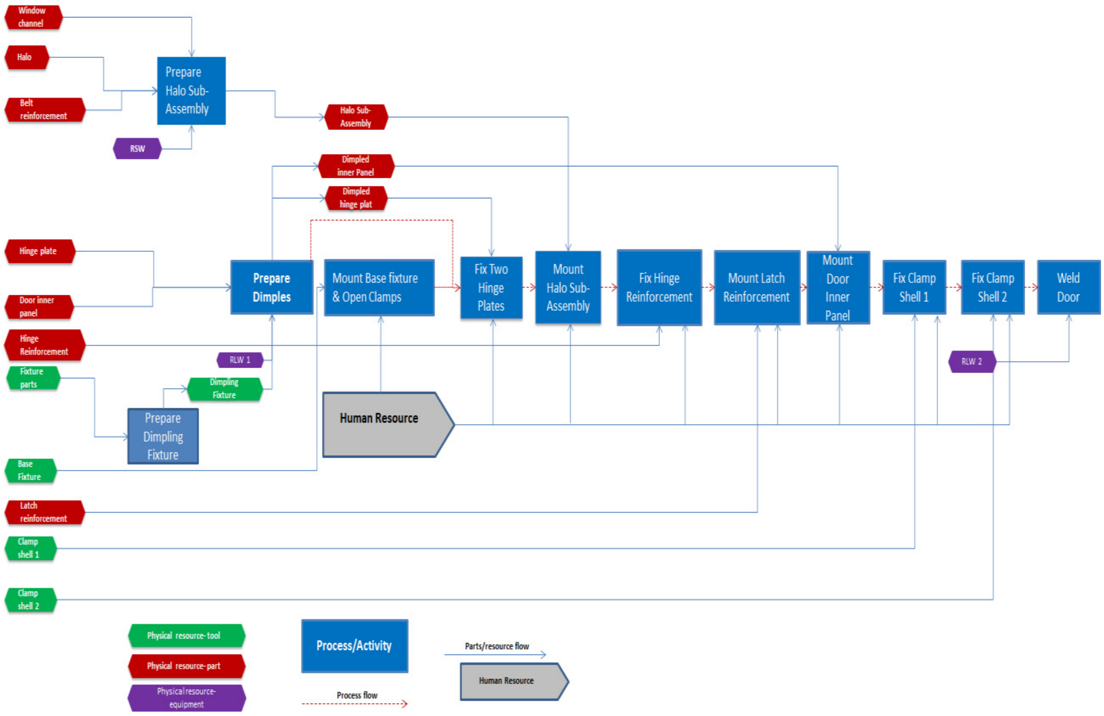

Fig. 2. Example process map for RLW doors (lab-based)

The parts model of the car door and associated feature decomposition is not included in this paper to maintain product confidentiality. As shown in figure 2, three door components are initially spot welded to form the halo-sub assembly. To maintain the appropriate minimum gap, door inner panels and hinge plates (which are components of the door) are dimpled. The hinge plates are then mounted unto the base fixture. The halo sub-assembly is then fixed on the hinge plate followed by the hinge reinforcement and then the latch reinforcement. The dimpled inner door is then mounted unto the assembled parts before the two clamp shells are clamped unto the base fixture.

To maintain a robust resource and cost database, the resource and cost information were populated unto the aPriori cost engineering platform to enable assessment of alternative product designs. To do this, typical production information such as production volume, target mass and batch sizes were indicated.

Step 2: Product feature correlation

In the next stage, product features and geometric cost drivers were linked with the process-resource-cost model. The product features have also not been disclosed in this paper for the sake of confidentiality. An example results obtained from when the aPriori workbench when populated with product features, processes, resources and cost data is shown in figure 3. The model allowed costing for the individual parts so that the impact of the component cost can be seen on the cumulative cost. Again for the sake of confidentiality, the figures presented here are not a true representation of the industrial case.

Step 3/4: GUI formulation and CAD importation

The GUI and CAD importation links were achieved through the Apriori workbench. The aPriori GUI was considered appropriate for describing the user information required to generate the cost information. Also the software allows various CAD format types to be imported into the aPriori workbench.

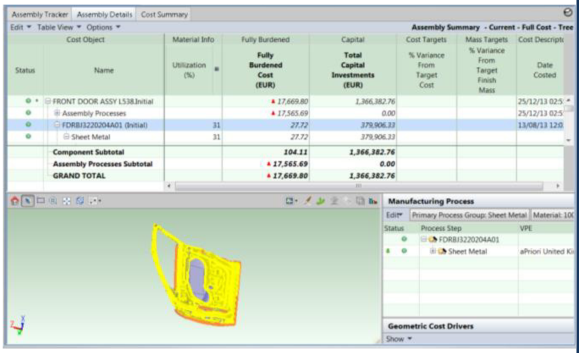

Fig. 3a. Example cost results

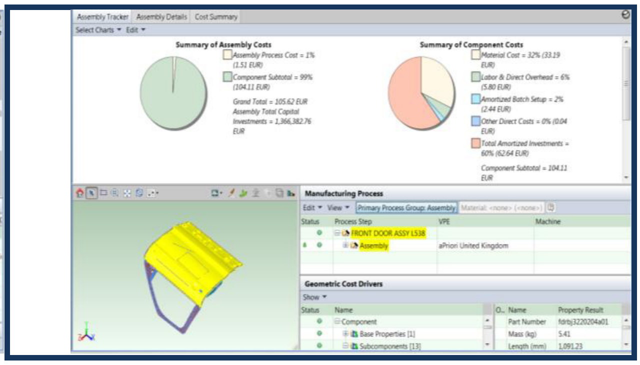

Fig. 3b. Cost components

5.1 Illustration of cost implication of engineering changes

In most manufacturing environments, engineering changes may either be product (e.g. product properties, product mix, product volumes, material availability, etc.), processes (e.g. capabilities, instances, logics, flow controls, roles and relationships) or resource related (e.g. competencies, capacities, controls and organisation). To experiment the effect of engineering changes on the manufacturing properties and cost, the authors undertook series of experiments but the example related to alternative stitch layout is shown in figure 4. The results show that the implementation of stitch type 1 (indicated as Previous) provides better cost indication than stitch type 2 (indicated as Current).

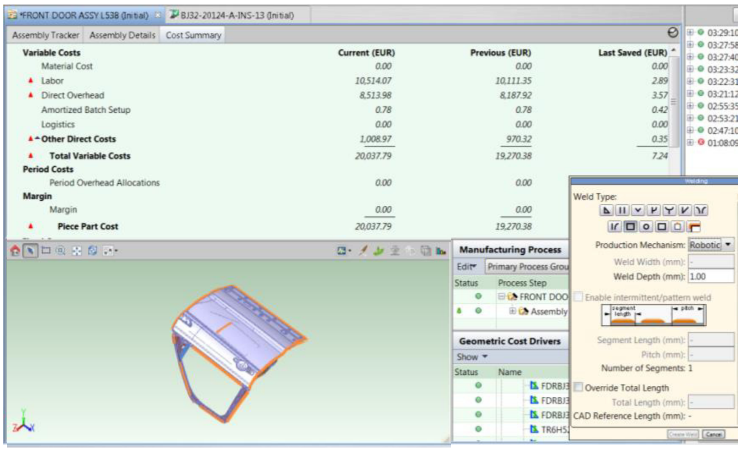

Fig. 4. Cost comparison of weld stitch types

6. Discussion of results and conclusions

The structure and initial application of the PPRC methodology has been presented in the previous sections. The show the cost implication of alternative stitch layouts (cost figures are not representative of the industrial scenario for the sake of confidentiality). In summary, the methodology:

- Considers product costing from a correlation of product features with process, resource and cost accounting data. The outcome of the research showed that product features can be integrated with process, resource and cost data so that cost related to alternative design and engineering decisions can be estimated at an early stage of the design process.
- Views products as being realised in a production environment which may be real or virtual

- Helps to economically justify the need for product, process and resource changes. This is particularly necessary for new product introduction where the cost implication of critical engineering design decisions have to be understood.

By integrating product features with process capabilities, resources and cost, designers and systems engineers can dynamically understand the implication of product design changes on process and resource utilisation, and ultimately the cost implication of such changes. It is uniquely important for engineering and manufacturing applications since dedicated manufacturing systems and customer facilities can be modelled such that alternative design decisions can be experimented before committing physical resources to realise them.

7. Future work

Research is currently ongoing to development the full correlations between different products, process and resource types as well as extending cost accounting data to reflect dynamic utilisation of resources. Also next actions include the verification and validation of the cost modelling data with industrial partners.

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