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## **A decision-support methodology for embodiment design and process chain selection for hybrid manufacturing platforms**

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Abstract:

This paper presents a methodology for the transformation of a product concept into a detailed design and manufacturing process chain for hybrid manufacturing platforms. Hybrid platforms offer new capabilities and opportunities for product design. However, they require high levels of process expertise for effective design and effective process selection. Design for hybrid manufacture is challenging as there is a requirement to understand a number of technologies, which may be highly varied. To address this challenge, a knowledge-based decision-support system developed in this paper enables manufacturing expertise to be integrated into procedures for product design and process chain selection. This formalised numerical methodology is able to consider a wider range of varied manufacturing processes than any previous study. A feature-based design method is developed, which guides the designer towards an optimised product design during the embodiment design phase, and a process-chain selection program is utilised to enable the effective analysis of a product design based on product evaluation criteria. The methodology has been successfully applied to the design of an LED product with internal geometries and electronics.

Key words:

Design for manufacture, process chain selection, hybrid manufacture, feature-based design, decision-support.

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## 1 Introduction

### Hybrid manufacturing definition

Hybrid manufacturing platforms integrate several varied manufacturing technologies into a single system in order to enable manufacturing of complex products. Zhu et al. [1] reviewed hybrid manufacturing and discussed its definition. They classified processes as additive, subtractive, joining and transformative and considered hybrid manufacturing as a combination of two or more manufacturing operations from different classifications. This differs from a traditional collection of processes in which all processes may be of the same classification. Chu et al. [2] also reviewed hybrid manufacturing and classified processes similarly. Studies have investigated novel combinations of manufacturing processes including additive and subtractive [3], subtractive and transformative [4] and additive and transformative [5]. There is growing industrial and academic interest and the number of commercial hybrid additive and subtractive processes has significantly increased since the late 2000s [6]. In the papers of Zhu et al. [1] and Chu et al. [2], only two of the reviewed studies considered processes from more than two categories [7,8]. Hybrid manufacturing platforms utilising processes from all four categories represent state-of-the-art research [9,10].

### Product design optimisation and process chain selection

Hybrid manufacturing platforms require equipment to interface the different processes and are more likely to have increased process idle times than traditional single-process manufacturing. However, they inherently avoid the cost and time associated with transferring a product between different manufacturing sites. There is large scope for optimisation of the design method and of the manufacturing routine. In order to ensure industrial competitiveness, it is critical that:

- the manufacturing process chain is optimised for a product
- product designs are optimised for manufacture through approaches such as design for manufacture

Several different combinations or sequences of manufacturing processes may be able to achieve the same product and therefore several manufacturing process chain options exist. For large numbers of process chains, computational analysis is required to support the choice of which process chain to use. Hence, process planning procedures have been the focus of extensive research, which is reviewed in Section 2.

In order to achieve the optimal product design for a hybrid manufacturing platform, the design must be tailored to that specific platform. Design for manufacture requires design decisions to have a focus on manufacturing capabilities [11]. For hybrid platforms, the designer may not have expertise in all of the manufacturing processes, which may vary greatly. Therefore there is a need to support design decisions that are made throughout the embodiment design process and guide the designer within manufacturing constraints [11,12].

#### Decision-support methodology for hybrid manufacturing

In order to facilitate design for manufacture (DfM) and process chain selection, methods for integrating product design and manufacturing capability data have been well studied and are reviewed in Section 2. However, these methods are generally constrained to specific processes or process ranges. Hybrid manufacturing presents a challenge to develop commonality between the highly varied processes. The review of hybrid manufacturing processes by Zhu et al. [1] concludes that there is a need for new process planning methods and for new modelling representations of hybrid process capabilities

This paper presents a novel coherent integrated methodology that formalises the integration of manufacturing capability data and product design data for hybrid manufacturing platforms. A case study demonstrates the use of the methodology for a state-of-the-art platform that utilises the widest range of process classifications incorporated in a single platform. The methodology enables the following three main benefits to improve competitiveness of hybrid manufacturing platforms:

- Optimise a design for manufacture by a hybrid manufacturing platform.
- Optimise the process chain to maximise the value of the manufactured product according to evaluation criteria.
- Enable an efficient overall process of translating a concept design into a process chain.

In this paper, Section 2 surveys the related works and Sections 3 - 6 describe the general methodology and the above benefits. The application of the methodology for a state-of-the-art hybrid manufacturing platform and a discussion are given in Sections 7 and 8.

## 2 Survey of related works

### Integration of product design and manufacturing capability data

The integration of manufacturing capability data and product design data is used in many concepts including design for manufacture, process chain selection, product design evaluation, toolpath planning and manufacturing cell formation. The different activities during product development require different types of expertise therefore studies have approached this integration of data from a range of viewpoints. Borja et al. [13] developed models for the product design and manufacturing data that enabled concurrent design work by people with different expertise and using different software. Liersch and Hepperle [14] developed an integrated framework to enable multidisciplinary collaboration for aircraft design. To achieve this they created a new data exchange file format called CPACS to establish communication between all disciplines. Jiang et al. [15] developed a collaborative methodology to support the design and evaluation of MEMS products.

Collaborative approaches rely on the integration of experts from different fields. For hybrid manufacturing platforms with highly varied processes, a collaborative approach may require a wide range of different expertise for a relatively small manufacturing platform. In order to be competitive, methods that can integrate manufacturing expertise into manufacturing capability models are important. Mutel and Ostrosi [16] developed a method for manufacturing cell formation based on the analysis of products' volumetric features. Feature recognition software was used to identify product features and potential combinations of machines that could manufacture the product. However, their methodology does not focus on supporting the design process or process chain selection for a given set of processes.

For hybrid manufacturing platforms with a defined set of processes, methodologies that support process planning within those specific processes and support DfM become more valuable. Ren et al. [17] developed an integrated process planning framework for hybrid manufacturing with additive and subtractive processes (direct metal deposition and CNC machining). Similarly, Zhu et al. [18] presented a process planning method for a hybrid additive and subtractive system (fused deposition modelling and CNC machining). Both studies focussed on splitting a geometric part into smaller volumes, for which the optimal manufacturing sequence was identified. Kerbrat et al. [19,20] presented a methodology to analyse the manufacturing complexity of a design for an additive and subtractive hybrid manufacturing system. Their approach represented a 3D geometric part through the division of space into small cuboid cells. This part representation was related to manufacturability indices for the additive and subtractive processes. A designer can use their methodology to identify volumes of a part that have the greatest impact on manufacturability. Although the designer is supported in the analysis of a 3D CAD product design, the presented method cannot be used to support the translation of a concept design into that initial 3D CAD model. This limitation also exists for the methodologies

of Ren et al. [17] and Zhu et al. [18], which similarly require the input of a 3D CAD model to enable analysis of a detailed design as opposed to supporting the early design stages.

Here, we present a method that reduces the need for manufacturing expertise during early embodiment design stages. All the above methodologies are strongly based on specific manufacturing processes or a specific combination of process types (e.g. additive and subtractive). They can be used for the analysis of volumetric product features but are not suitable for more broad combinations of processes and product features. For example, the micro assembly of bought-in components, planar printed elements or surface functionalisation.

### Process chain selection

Many studies have investigated approaches that may be used to identify and evaluate process chains. Thibault et al. [21] presented schemas to identify process plans specifically for forging processes. Skóra et al. [22] also studied forging technologies and implemented finite element simulations of tool wear and stress distribution into a process chain selection procedure. Hansen and Büttgenbach [23] present a process sequence analysis method for MEMS device based on process or material incompatibilities and manufacturing technology capabilities. However, these methods were developed for specific technologies and are not applicable to a general hybrid manufacturing platform.

Blanch et al. [24] give a detailed description of the activities required to generate process chains for a given product design. Processes are first filtered based on their ability to fulfil critical product requirements. If some product requirements remain unfulfilled after the first process, subsequent processes are identified. This procedure continues until all alternative process chains that can achieve all product requirements are identified. The study of Petersen and Gausemeier [25] presents a similar method with a focus on functional graded components. Gindy et al. [26] presented a framework for the taxonomy of product features to facilitate process planning to minimise the number of part/machine reconfigurations. Zhao et al. [27] reviewed research into feature recognition from purely geometric 3D CAD models (STEP) and subsequent process planning. They demonstrate that this is an active research area that has been developing over two decades.

The above studies are strongly focussed on the volumetric geometries of a design or they are not applicable to hybrid manufacturing with highly varied process types and product features. In addition, they all require a fully-dimensioned 3D model of the design as an input to the methodologies and are not focussed on supporting a DfM approach to translate an initial product concept into a manufacturable detailed-design.

### Design for manufacture

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A well-trusted method to achieve this guidance is through a feature-based design tool. Such tools are used frequently in decision support systems. Qian and Dutta [28] presented a feature-based design method for heterogeneous objects made from functionally graded materials. Yetukuri et al. [29] developed an integrated tool for CAD, CAM and CAE activities specifically for the Gas Metal Arc Welding process. Abdalla and Knight [30] developed an expert system for the concurrent product and process design of mechanical parts. Several feature-based design methodologies have focussed on MEMS devices. Liu et al. [31] developed an approach to relate product function to product geometry to a manufacturing mask for micro devices. Similarly Liu and Chen [32] developed a hierarchical design method for silicone-based micro devices that enabled optimisation of the design structure. In all cases, the methods were developed for specific process or product types. They cannot be applied to a hybrid manufacturing platform with highly varied technologies.

Ferrer et al. [33] presented a general methodology to identify the information required to support a DfM approach. Their method helps a designer to identify a relationship between design and manufacturing information but it is necessary for them to have a level of manufacturing expertise. For hybrid manufacturing platforms with numerous and highly varied processes, there is a need for DfM approaches in which the designer is not required to have expertise in all the technologies

### Presented methodology

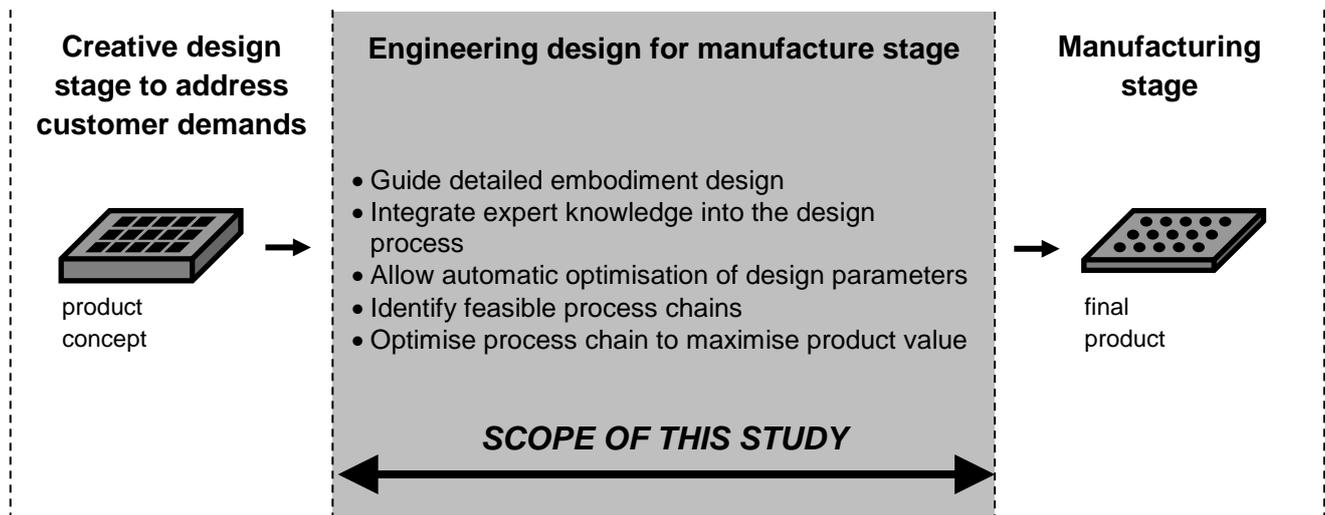
State-of-the-art hybrid manufacturing platforms integrate a wider range of processes than in traditional manufacturing. Methodologies that support process planning or design for manufacture are typically developed for a specific set of technologies or limited to volumetric design features. Furthermore, very few approaches support both design for manufacture and process chain selection. No methodologies exist that support feature-based design and process chain selection for the wide range of process types in state-of-the-art hybrid manufacturing platforms. We build on the existing research to include capability for a wider range of product features than previously studied. The methodology presented here supports feature-based design and process chain selection, whilst accommodating features that are volumetric as well as functional features such as surface functionalisation or planar features.

## **3 Overview of the process planning methodology**

The methodology presented here translates a product concept into an optimal design and identifies the most suitable process chain. The methodology includes three models which capture information about:

- the product design
- hybrid platform manufacturing capabilities
- product evaluation methods

The modelling methodology is focussed on the embodiment design stage and the selection of manufacturing processes as shown in Fig. 1. Preliminary conceptual design is not incorporated since it should not be influenced by manufacturing capabilities. In contrast, embodiment design should consider the capabilities.



**Fig. 1** Focus and scope of the process planning methodology includes design for manufacture, design optimisation and process chain selection.

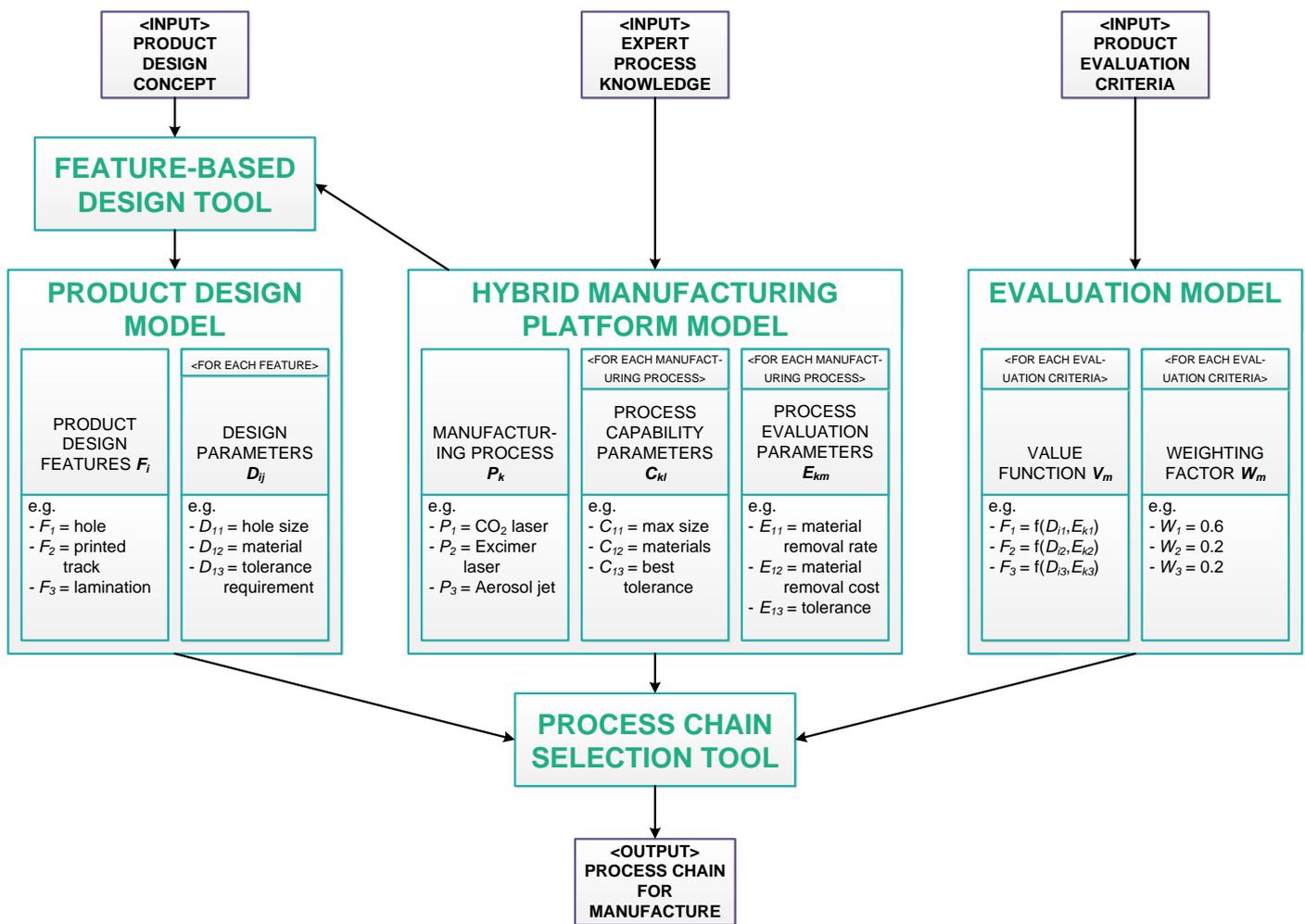
The modelling methodology consists of a **Product Design Model**, a **Hybrid Manufacturing Platform Model** and an **Evaluation Model**, which link the product design to manufacturing knowledge and product evaluation methods. An overview of the contents of these three models is given in Fig. 2. More detail about individual parameters is given in the next section of this study. In addition to the models, a **Feature-Based Design Tool** is used to produce the *Product Design Model* and facilitate design for manufacture. Also, a **Process Chain Selection Tool** is used to analyse the models and identify the optimal process chain.

The **Product Design Model** describes the product through design parameters in order to enable the selection of the most suitable manufacturing processes. These are selected to achieve the best overall product value in terms of the product requirements as set out by the product developer. Specific feature-types are developed in the model in order to control the format and transfer of design information. They also enable the designer to be guided towards a product design that is technologically achievable. Example feature-types include an electrically conductive track, a flat-bottomed recess, a through-hole and the insertion of a bought-in component. The overall product model is described by a series of features, each with a number of design parameters. The structure of the *Product Design Model*, and therefore information about which design parameters are required for each feature-type, are specified by manufacturing process experts. In order to translate a product concept into the *Product Design Model* format, a *Feature-Based Design Tool* is integrated

into a CAD package. The design tool integrates expert knowledge into the design for manufacture activity and enables the designer to achieve a product design that is optimised for the manufacturing capabilities.

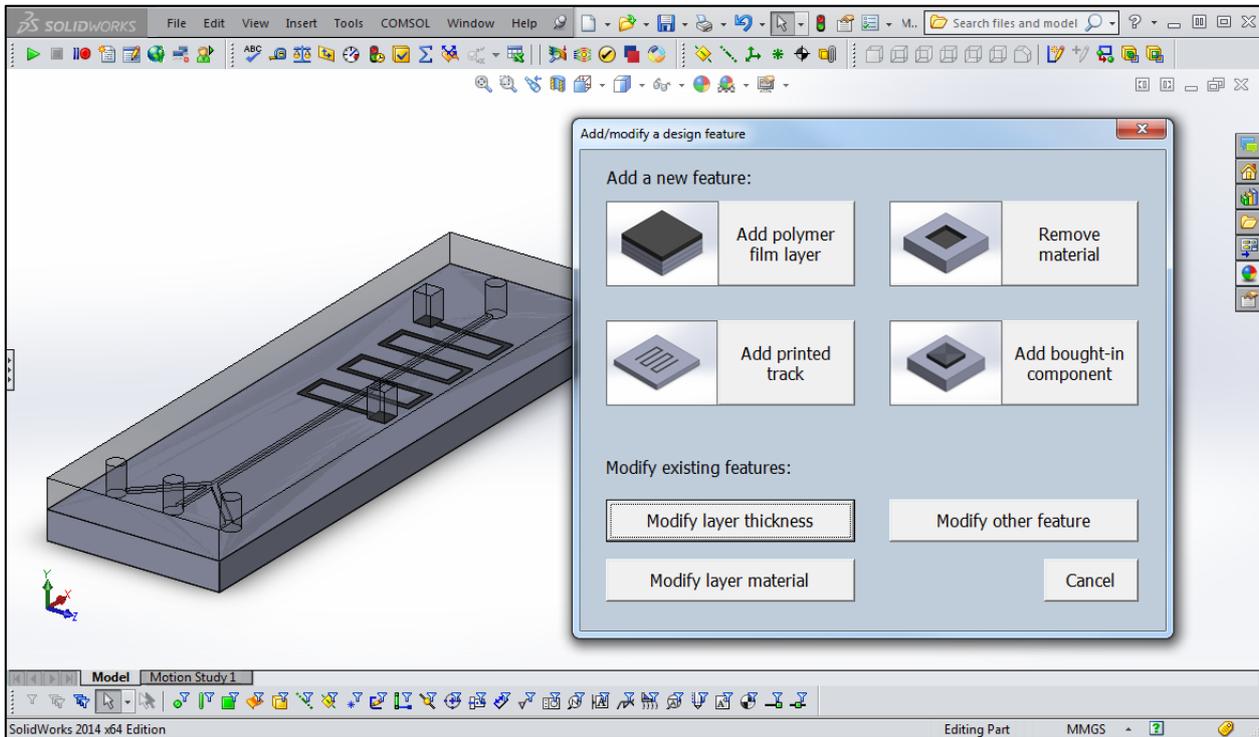
The ***Hybrid Manufacturing Platform Model*** describes the capabilities of the manufacturing processes being considered for manufacture of the product. The model describes the manufacturing processes in a structured quantitative format which enables comparison to the design parameters. Process capabilities indicate whether a feature can be manufactured or not, whereas evaluation parameters describe how successfully a process fabricates a product feature according to product evaluation methods. The ***Hybrid Manufacturing Platform Model*** enables the analysis of manufacturing process chains and enables the ***Feature-Based Design Tool*** to guide the designer to within manufacturing capabilities.

The ***Evaluation Model*** describes the evaluation criteria for the product such as manufacturing time, tolerance, cost or ecological factors. Each evaluation criterion is non-dimensionalised, numerical and weighted with respect to other criteria in order to allow an overall product value to be calculated. The value functions, which relate quantitative product or manufacturing details to overall product value, are set up by the product developer with support from an engineer familiar with the hybrid manufacturing platform.



**Fig. 2** Overview of the methodology including the models used to represent the product design, the manufacturing capabilities and the method of evaluation. The parameters given for each model are explained in Section 5.

A **Feature-Based Design Tool** is used to translate a design concept into a detailed product design during the embodiment design phase and to generate the *Product Design Model*. Guidance is offered to the design engineer to facilitate a design for manufacture approach and prevent unfeasible design choices. This enables a more efficient design process and reduces the number of product design iterations. The *Feature-Based Design Tool* is integrated into a 3D CAD package; the design engineer is presented with a pop-up user interface in order to add new features to a design as shown in Fig. 3. When a new feature is selected, the design engineer is presented with several feature-options, such as achievable depths and materials for a printed conductive track. The information regarding feasible feature-options is accessed in the *Hybrid Manufacturing Platform Model*. The product design information is automatically recorded by the *Feature-Based Design Tool* as a *Product Design Model*.



**Fig. 3** The feature-based design tool is integrated into a 3D CAD package. It offers the design engineer feature-types that can be manufactured by a specific hybrid manufacturing platform.

The **Process Chain Selection Tool** uses the three models described above to select the best combination of manufacturing processes to fabricate the product. These generate the highest product value according to the evaluation criteria set by the product developer. The basic process chain selection methodology consists of three stages:

1. Identify which manufacturing processes can be used for each product feature.
2. Identify all feasible combinations of processes.
3. Analyse which process chain results in a product of the greatest value.

For step 1, the *Product Design Model* is analysed feature-by-feature in relation to the expert knowledge in the *Hybrid Manufacturing Platform Model*. For step 2, the list of possible process chains is generated based on which manufacturing processes can achieve each feature and compatibility between processes. Step 3 analyses each process chain option according to the *Evaluation Model* to identify the value of the product and selects the chain that achieves the highest value. More complex methods for optimisation of the process chain are discussed later in this paper.

#### **4 Activities to implement the methodology**

This section describes the activities that are necessary when a new hybrid manufacturing platform is developed or a new product is manufactured.

##### A: New manufacturing platform activities

The initialisation of a new hybrid manufacturing platform requires several one-off activities:

- A1. The *Hybrid Manufacturing Platform Model* is developed by process experts.
- A2. Information required in the *Product Design Model* is identified by process experts.
- A3. Feasible feature-types are programmed into the *Feature-Based Design Tool*.
- A4. The *Process Chain Selection Tool* is adapted to the platform.

For technologies that have been implemented in previous platforms, their models are adapted to the new platform with minimal effort.

##### B: New product activities

For each new product, the following activities are undertaken:

- B1. Generate the *Evaluation Model* according to the product developer's design specification. An *Evaluation Model* may be applicable to several products or product variants with little or no modification.
- B2. Create the *Product Design Model* by designing the product in the *Feature-Based Design Tool*.
- B3. Select the optimal process chain using the *Process Chain Selection Tool*.

For products that require state-of-the-art fabrication, the manufacturing knowledge may not exist for particular product features. In which case, an extra activity is required to conduct manufacturing trials and update the *Hybrid Manufacturing Platform Model*. The final selected process chain is reviewed by the design engineer and process experts. The product developer approves the expected product and process experts set up the manufacturing routine.

## 5 Parameters used in the methodology

The parameters for the three models (*Product Design Model*, *Hybrid Manufacturing Platform Model* and *Evaluation Model*) are described in the following text, supported by Fig. 4 which exemplifies their use. The figure shows how model parameters are used in the main steps of a process chain selection procedure. The three methodology models are used as inputs. The figure is not intended to be a fully functional program flowchart; its purpose is to demonstrate the use of the parameters.

### Product Design Model

- **Product features,  $F_i$** , are design aspects of a product such as a solid body of material, a hole or an electronic circuit. A product can be broken down into and fully described by its features.
- **Design parameters,  $D_{ij}$** , describe the details of each of the product features in order to assess which manufacturing processes should be used to manufacture each feature. Examples are feature dimensions, substrate material and tolerance requirements.  $D_{ij}$  is the  $j$ th design parameter for the  $i$ th product feature.

The  $i$  index indicates the feature.

The  $j$  index indicates the design parameter.

### Hybrid Manufacturing Platform Model

- **Manufacturing processes,  $P_k$** , are the processes included in the hybrid manufacturing platform that are considered for use during manufacture of each product feature.
- **Process capability parameters,  $C_{kl}$** , define the capabilities of a manufacturing process. Examples are maximum working dimensions, minimum feature size, best achievable tolerance and acceptable materials.  $C_{kl}$  is the  $l$ th capability parameter for the  $k$ th manufacturing process.
- **Process evaluation parameters,  $E_{km}$** , give details about the performance of a manufacturing process in order to evaluate the value of the product based on which manufacturing processes are used. They describe the process performance for each of the evaluation criterion such as material removal rate, operational cost, tolerance, environmental factors, reliability, etc.).  $E_{km}$  are the evaluation parameters for the  $m$ th evaluation criterion of the  $k$ th manufacturing process. The difference between capability parameters and process evaluation parameters is that the former are used to determine whether a process can be used to manufacture a specific product feature whilst the latter are used to determine how well the process is able to manufacture the feature.

The  $k$  index indicates the manufacturing process.

The  $l$  index indicates the capability parameter.

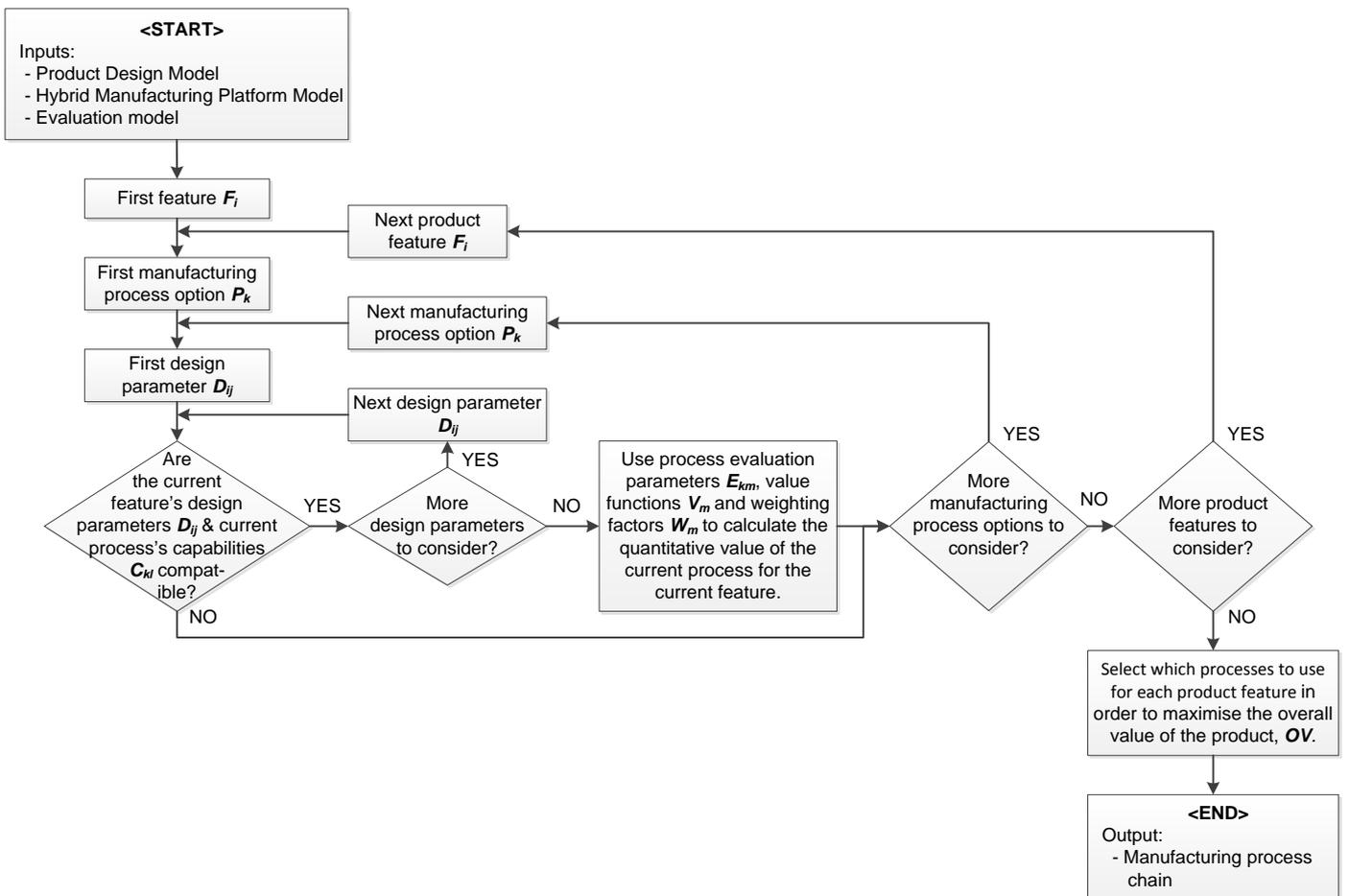
The  $m$  index indicates the evaluation criterion.

Evaluation Model

- **Value functions,  $V_m$** , are user-defined functions that indicate how the value of product is related to the measurable evaluation parameters. There is a value function for every evaluation criterion.  $V_m$  is the value function for the  $m$ th evaluation parameter.
- **Weighting factors,  $W_m$** , specify the relative importance of different evaluation criteria.  $W_m$  is the weighting of the  $m$ th evaluation criterion.
- **Overall Value,  $OV$** , is calculated by multiplying the value functions  $V_m$  with the respective weighting factors  $W_m$ .

Value functions,  $V_m$ , vary considerably between customers and between evaluation criteria. However, the output of a value function should be non-dimensional and have a value between 0 and 1, where 0 indicates unacceptable and 1 indicates optimal. A value function for cost is likely to consider the summation of costs over the entire product. In contrast, the value function for tolerance may be based on the worst tolerance at any point in the product. It may be beneficial for evaluation criterion to be weighted towards particular features. Such extensions are achieved by either having different weighting factors for each feature ( $W_m$  becomes  $W_{im}$ ) or different value functions for each feature ( $V_m$  becomes  $V_{im}$ ). The final process chain is selected as that which maximises the  $OV$  rating of the product.

A decision-support methodology for embodiment design and process chain selection for hybrid manufacturing platforms



**Fig. 4** Parameters used in the model are exemplified in this process chain selection procedure. The procedure can be readily implemented as a computer program because the parameters of the methodology describe all necessary details of the product design, the hybrid manufacturing platform and product evaluation methods.

## 6 Advantages of using the modelling methodology

The overall structure of the methodology has been presented in the previous section. In this section, the following three benefits, which are realised by using the methodology, are discussed:

- Optimise the product design for manufacture.
- Optimise the manufacturing process chain to maximise product value.
- Reduce the time taken to translate a product concept into a detailed product design and manufacturing process chain.

### 6.1 Optimisation of the product design for hybrid manufacture

Product design optimisation (to maximise the overall value,  $OV$ , of the product) is achieved designing the product in the *Feature-Based Design Tool*. Depending on the level of guidance desired, the designer can be (i) given real-time guidance as to whether the design parameters  $D_{ij}$  are achievable by the manufacturing capabilities  $C_{kl}$ , or (ii) offered a range of feasible design parameters from which to choose. For example, the designer may only be permitted to design a hole depth within an achievable range dictated by the capability parameters  $C_{kl}$  for the hybrid manufacturing platform. A constrained design method reduces creativity but accelerates the design process and enables design for manufacture with little or no expert manufacturing knowledge.

In addition to advising the designer on manufacturing feasibility, the design tool also presents product-value-related information such as the min/max costs (based on process evaluation parameters  $E_{km}$ ) associated with the manufacture of each product feature. This enables the designer to understand the effect of their design decisions during embodiment design. The design tool may also suggest minor design improvements or propose design variants.

The methodology presented in this study enables several other design optimisation methods. The designer can produce several design variants and compare  $OV$  to identify the optimal design variant. Also, the designer is able to spend more time on design tasks rather than on the manual analysis of the designs because the process chain selection procedure conducts this analysis automatically. They may therefore be able to produce several more design variants for the same time-effort. Parametric optimisation of a product design can be achieved by enabling design parameters such as material types or hole diameters to be varied automatically within boundaries set by the designer. Following this, the process chain selection routine optimises the design parameters in order to maximise  $OV$ .

## **6.2 Optimisation of the process chain and process sequence**

The methodology enables automatic analysis of alternative process chains and therefore enables a larger number of chains or more details to be analysed than would be possible manually. In the simplest implementation of the methodology, the sequence in which product features are manufactured is manually identified. However, several alternative feature manufacturing sequences may be identified by (i) manually specification of several alternative sequences; (ii) using feature manufacturing sequence rules describing which features depend on other features. In the most simplistic example, a printed track within a recess cannot be printed until the recess is machined; or (iii) computational analysis of the *Product Design Model* to identify several alternative process sequences. The automatic identification and analysis of process sequences may enable a product to be manufactured with a greater *OV* rating.

## **6.3 Overall procedure efficiency**

The methodology enables an efficient overall process of translating a product concept into a manufacturing process sequence in several ways:

- There is an efficient transfer of information (e.g. CAD data and process chain data). This reduces the risk of human error and enables the most effective use of human resources.
- The set-up of manufacturing processes is significantly accelerated since CAD files and process parameters can be automatically supplied to the process engineer in the required format.
- The design tool prevents unfeasible product designs and therefore reduces the number of design iterations.
- Process chain identification and analysis is automated. This is a time-consuming task if completed manually.

All these efficiency benefits reduce the time taken for the overall transformation of a product concept into a manufacturing process chain. This time-saving can either directly save costs or be used to further optimise a product design or process chain. In both cases the ultimate aim is to improve competitiveness.

## 7 Application of the methodology for the SMARTLAM manufacturing platform

The general methodology described above was implemented here for a hybrid manufacturing platform that was developed in the EU FP7 SMARTLAM project. The methodology was used for embodiment design of a concept LED product and selection of the optimal manufacturing process chain. The following sections give details of this implementation.

### 7.1 Platform initialisation

Following the outline given in Section 4, activities A1 to A4 were completed to initialise the models and tools of the methodology. Manufacturing capabilities were assessed and recorded as the *Hybrid Manufacturing Platform Model* and the design tool and process chain selection tool were created.

#### 7.1.1 Hybrid manufacturing platform processes

The hybrid manufacturing platform developed in the EU FP7 SMARTLAM project is shown in Fig. 5. It includes the following six manufacturing processes,  $P_k$ :

$P_1$ : Excimer laser machining

$P_2$ : CO<sub>2</sub> laser machining

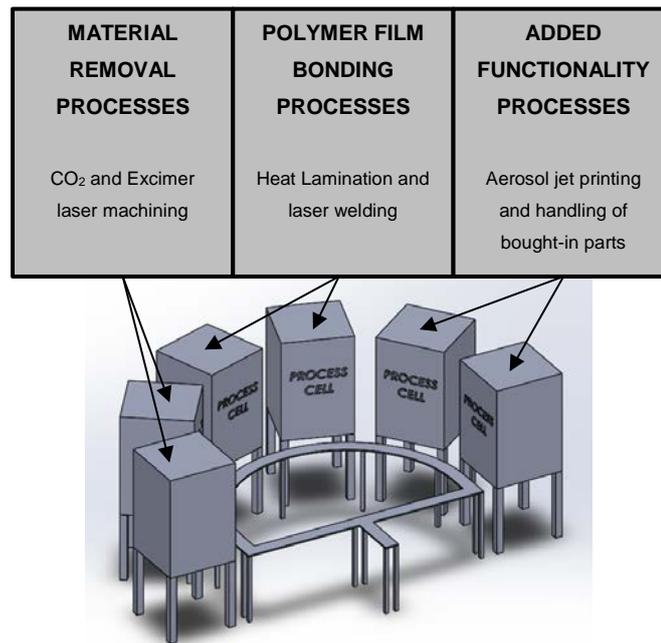
$P_3$ : Diode laser welding

$P_4$ : Polymer film heat lamination

$P_5$ : Aerosol jet printing

$P_6$ : Pick and place of bought-in components and adhesive application

Products are manufactured by laminating or welding several layers of polymer film together. The polymer films can be of a range of thicknesses from 100 to 500  $\mu\text{m}$ . The polymer films are often processed before bonding in order to embed functionality. Products with complex functionality and microscale features are ideal for the platform. A traditional manufacturing approach for such products would involve in several stages at several different sites. The platform is configured for polymer film sheets of size 150 x 150 mm.



**Fig. 5** The hybrid manufacturing platform builds-up polymer film layers utilising processes for bonding, laser machining, aerosol jet printing and handling bought-in components.

### 7.1.2 Hybrid manufacturing platform model

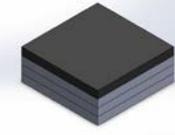
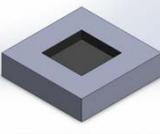
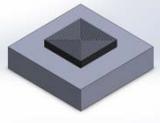
Product features that could be achieved by the hybrid manufacturing platform were as follows:

- remove material volume ( $k=1,2$ )
- add new polymer film layer ( $k=3,4$ )
- produce electrically conductive track ( $k=5$ )
- add bought-in component ( $k=6$ )

where  $k$  indicates the process ID number of suitable manufacturing process. Machining trials were completed to determine capability parameters  $C_{kl}$  and evaluation parameters  $E_{km}$ . These are given in Table 1. Processes were grouped according to the feature-types they can fabricate since the manufacturing information required in the model varied for each type. The *Hybrid Manufacturing Platform Model* was accessed by the *Feature-Based Design Tool* and *Process Chain Selection Tool* through HTTP requests. Manufacturing capabilities were assessed based on geometric, materialistic and weight limitations. The polymer film area was limited to the working area of the platform; *remove material volume* and *produce electrically conductive track* features did not require capability parameters for maximum size since processing is only possible within the polymer film area. Bought-in components were limited to the maximum size and weight that can be handled by the suction-cup gripper used in the platform. All feature-types had material capabilities either due to machinability factors or compatibility between materials (e.g. bonding between two polymers or adhesion of the printed

track). Evaluation parameters were chosen to enable the calculation of manufacturing time, cost and tolerance for each feature.

**Table 1** The capability parameters and evaluation parameters of the *Hybrid Manufacturing Platform Model* are detailed for the four feature-types.

<i>Feature-type</i>	<i>Hybrid Manufacturing Platform Model Parameters</i>	<i>Parameter value</i>
Add new polymer film layer.  Diode laser and lamination. Process number $k=3,4$ .	$C_{k1}$ Suitable materials $C_{k2}$ Minimum film thickness $C_{k3}$ Maximum film thickness $C_{k4}$ Maximum film width/length	Wide range 100 $\mu\text{m}$ 500 $\mu\text{m}$ 150 mm
	$E_{k1}$ Bonding time $E_{k2}$ Bonding cost per minute $E_{k3}$ Inter-layer tolerance	Material dependent ( $\text{mm}^2/\text{min}$ ) 1.8 $\text{£}/\text{min}$ ( $k=3$ ) or 1.5 $\text{£}/\text{min}$ ( $k=4$ ) Material dependent ( $\mu\text{m}$ )
	$C_{k1}$ Suitable materials $C_{k2}$ Minimum depth $C_{k3}$ Minimum recess width	Polymeric 10 $\mu\text{m}$ 20 $\mu\text{m}$
Remove material volume  Excimer and $\text{CO}_2$ lasers. Process number $k=1,2$ .	$E_{k1}$ Machining rate $E_{k2}$ Machining cost per minute $E_{k3}$ Machining tolerance	Material dependent ( $\text{mm}/\text{min}$ or $\text{mm}^3/\text{min}$ ) 2.0 $\text{£}/\text{min}$ ( $k=1$ ) or 1.5 $\text{£}/\text{min}$ ( $k=2$ ) Material dependent ( $\mu\text{m}$ )
	$C_{51}$ Suitable substrate materials $C_{52}$ Suitable print materials $C_{53}$ Minimum track height $C_{54}$ Minimum track width	Wide range Wide range 30 nm 10 $\mu\text{m}$
	$E_{51}$ Printing rate $E_{52}$ Printing cost per minute $E_{53}$ Printing tolerance	Material dependent ( $\text{mm}^3/\text{min}$ ) 2.0 $\text{£}/\text{min}$ Material dependent ( $\mu\text{m}$ )
Add bought-in component.  Process number $k=6$ .	$C_{61}$ Suitable materials for adhesion $C_{62}$ Max component weight $C_{63}$ Min suction-region width $C_{64}$ Max component size	Wide range 6.4 g 250 $\mu\text{m}$ Not constrained
	$E_{61}$ Insertion time per component $E_{62}$ Insertion cost per minute $E_{63}$ Insertion tolerance	8 s 1.2 $\text{£}/\text{min}$ 10 $\mu\text{m}$

### 7.1.3 Design tool and process chain selection tool

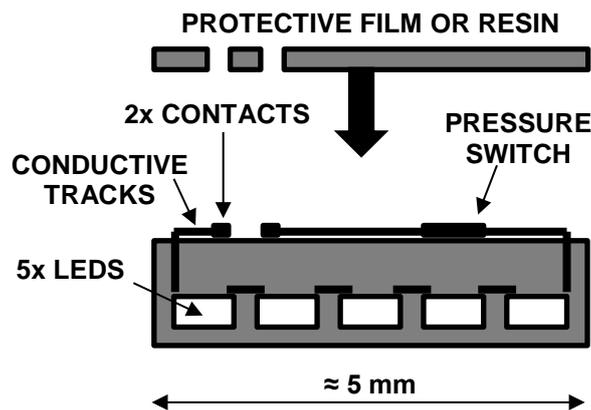
A *Feature-Based Design Tool*, shown in Fig. 3, was programmed within SolidWorks 2014 in order to produce the *Product Design Model* and offer design guidance. The designer was taken through a series of user-interface windows to create each new feature. In the hybrid manufacturing platform, products are built up layer-by-layer through the addition of polymer films. Therefore, the designer created a product by adding several polymer film layers in the CAD package. Once layers were created the designer was able to add features to remove volumes of material from the layers or printing conductive tracks onto the surfaces. Bought-in components, such as LEDs, could also be included in the design. This involved importing and positioning their 3D CAD models. The process chain selection tool was programmed in MATLAB. It accessed the *Product Design Model*, *Evaluation Model* and *Hybrid Manufacturing Platform Model* and output the optimal manufacturing process chain.

## 7.2 Product design and analysis

Activities B1 to B3 in Section 4 are demonstrated here for the design and evaluation of the LED product. During these activities, the *Evaluation Model* and *Product Design Model* were generated and subsequently used in the *Process Chain Selection Tool*.

### 7.2.1 Product design concept: LED light film

Fig. 6 shows a concept design for an LED light film. This is used as an input for the detailed embodiment design process. Five LEDs and a pressure switch are encapsulated within a polymer. External contacts are provided to supply power. The polymer material must be transparent below the LEDs and all conductive tracks must either be embedded or protected by a resin coating. The LEDs and pressure switch components are defined explicitly by the product developer, along with the conductive track width, height and material. To ensure a good electrical connection to the LED chips, a positional tolerance of 50  $\mu\text{m}$  is required.

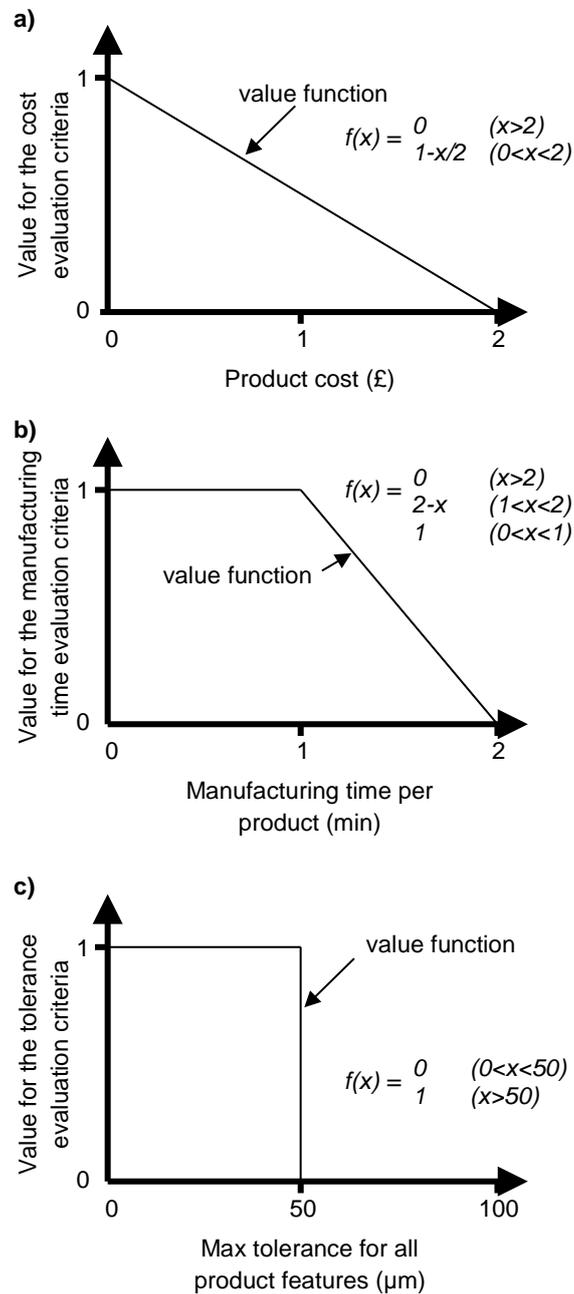


**Fig. 6** Concept LED light film product containing 5 embedded LEDs and a pressure switch.

### 7.2.2 Evaluation model

The *Evaluation Model* considered overall product cost, manufacturing time and tolerance based on the functions given in Fig. 7. Cost value was 1 when overall product cost was £0 and linearly decreased to zero as cost increased to £2. For manufacturing time, a value of 1 was used when manufacturing time per product was less than 1 minute, representing 4800 products manufactured in two weeks, and linearly decreased to zero when the manufacturing time increased to four weeks for 4800 products. For tolerance, a step function was used in which features with tolerances larger than 50  $\mu\text{m}$  scored zero. Regardless of the chain's overall value, if any of the evaluation criterion were found to be zero the whole chain was rejected. This was necessary since, for example, reducing cost at the expense of manufacturing time may have resulted in a higher overall value being calculated but if the products were not manufactured within the maximum time

frame, they have no value. Cost was weighted 80% and manufacturing time weighted 20%. Tolerance was not weighted because it was a step function.



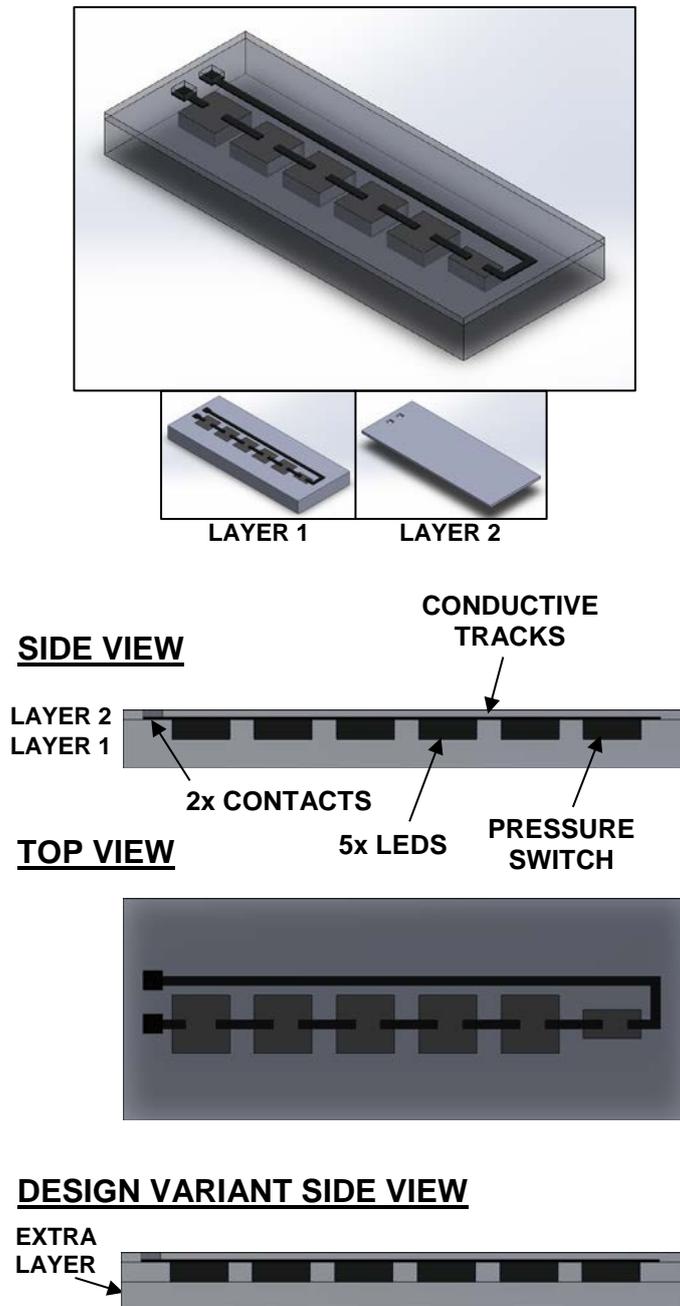
**Fig. 7** Example value functions for a) total product cost, b) manufacturing time and c) maximum tolerance.

### 7.2.3 Embodiment design and the product design model

The *Feature-Based Design Tool* was used to generate a feasible design for the LED product. The design is shown in Fig. 8. During the embodiment design phase, the dimensions, materials and detailed product layout were decided. The steps taken during the design process were as follows:

- create layer 1 from polyethylene terephthalate (PET)
- insert pockets to hold the 5 LEDs
- insert pocket to hold the pressure switch
- insert the LEDs
- insert the pressure switch
- insert the printed track to connect the LEDs and pressure switch
- create layer 2 from PET
- insert the through-holes for access to the electric contacts

The design tool recorded information that was input by the design engineer regarding the product features as the *Product Design Model*. The design parameters that were recorded for the features in layer 1 of the LED product are given in Table 2.



**Fig. 8** The LED product design created using the *Feature-Based Design Tool*. Two polymer film layers encapsulate five LEDs, a pressure switch and a printed circuit. A design variant is created with three layers instead of two as suggested by design guidance in the design tool.

**Table 2** Design parameters for the features in layer 1 of the LED product.

<b>Feature</b>	<b>Product Design Model Parameters</b>	<b>Parameter values for layer 1 in the design (excluding pressure switch)</b>
Add polymer film layer (layer 1)	D <sub>11</sub> Layer material D <sub>12</sub> Layer thickness D <sub>13</sub> Layer length D <sub>14</sub> Layer width D <sub>15</sub> Layer number D <sub>16</sub> 2D drawing ID / CAD file (layer outline)	PET 500 µm 5.85 mm 2.30 mm 1 Layer outline drawing
Remove material volume (LED chip recesses)	D <sub>21</sub> Layer number D <sub>22</sub> Layer material D <sub>23</sub> Through full polymer film thickness? D <sub>24</sub> Cut-out depth D <sub>25</sub> Cut-out area D <sub>26</sub> Cut-out perimeter D <sub>27</sub> From top/bottom face D <sub>28</sub> 2D drawing ID / CAD file (recess shape)	1 PET No 200 µm 1.80 mm <sup>2</sup> 12.0 mm Top LED pocket drawing
Produce electrically conductive track	D <sub>61</sub> Layer number D <sub>62</sub> Substrate material (polymer film layer) D <sub>63</sub> Conductive track material D <sub>64</sub> Conductive track height D <sub>65</sub> Conductive track width D <sub>66</sub> Conductive track volume D <sub>67</sub> 2D drawing ID / CAD file (track layout)	1 PET Silver 2.0 µm 100 µm 1.98 x10 <sup>-3</sup> mm <sup>3</sup> Conductive track drawing
Add bought-in component (LED chips)	D <sub>41</sub> Layer number D <sub>42</sub> Substrate material (polymer film layer) D <sub>43</sub> Weight D <sub>44</sub> Length D <sub>45</sub> Width D <sub>46</sub> Height D <sub>47</sub> Bonding surface material D <sub>48</sub> Part ID / CAD file D <sub>49</sub> Coordinate location (x, y, z, θ <sub>x</sub> , θ <sub>y</sub> , θ <sub>z</sub> )	1 PET 0.15 mg 500 µm 500 µm 200 µm Silicon wafer LED CAD file ID LED positions

#### 7.2.4 Design guidance and process chain selection

Guidance was offered to the design engineer in several ways during the design of the LED product. As an example, the *remove material volume* feature is discussed here in relation to the pockets for LED chips. Similar guidance was also offered for the rest of the feature-types. Guidance was offered through pop-up windows displaying warnings or recommended modifications.

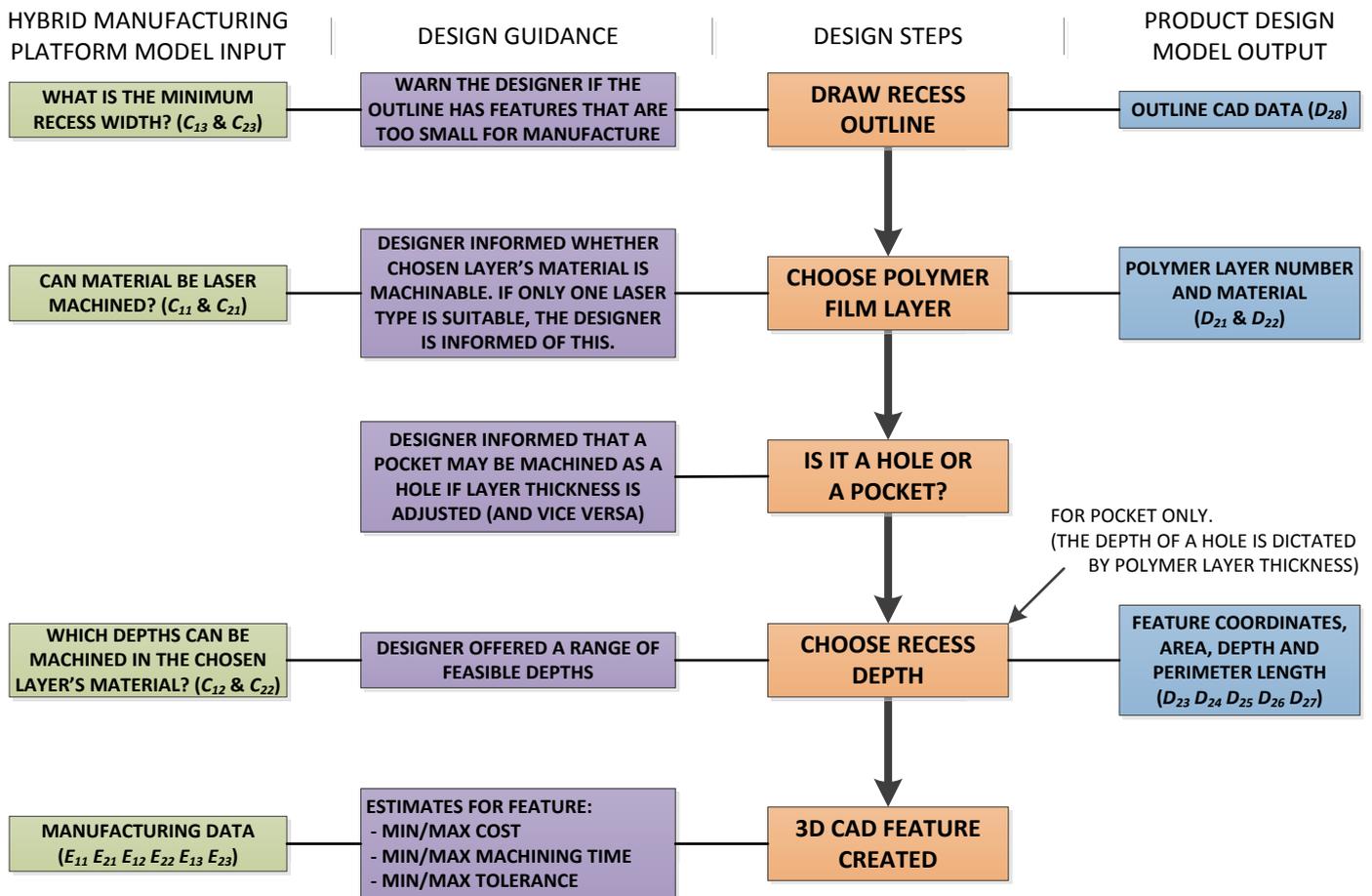
The design steps taken to create the pockets for housing the LEDs are shown in Fig. 9. The figure shows how design guidance is provided and how data is input/output. After drawing the outline of the pockets in the CAD package, all design steps were completed by navigating through the pop-up windows of the design tool. The design tool first prompted the designer to select their pocket outline drawing. A preliminary check of the sketch ensured the capability parameters for minimum recess width were adhered to ( $C_{13}$  and  $C_{23}$ ). Next, the designer selected the polymer film layer into which the pockets were to be machined and material capabilities were assessed ( $C_{11}$  and  $C_{21}$ ). They were advised that the material choice of PET may reduce the overall product value because it can only be machined by the Excimer laser (CO<sub>2</sub> laser gave poor quality results in

PET trials). By varying the material choice through several options, the designer found that the machinability benefit of polymethyl methacrylate (PMMA) outweighed the greater raw material cost disadvantage versus PET, and therefore enabled a higher product value to be achieved.

A *remove material volume* feature could be a through-layer-thickness *hole* or a partial-layer-thickness *pocket*. For a *hole*, the perimeter is cut to release the interior material whole, whereas for a *pocket* the full amount of material must be laser milled. The method of calculating machining time differs for *pockets* and *holes*. Therefore the design parameters for this feature-type include both the area and perimeter of the removed material. In the final design steps, the designer indicated that the recesses were *pockets* with a depth of 200  $\mu\text{m}$ . The depth was within the manufacturing capabilities ( $C_{12}$  and  $C_{22}$ ). The designer was advised that greater overall product value may be achieved by using two layers instead of one, to enable a *hole* instead of a *pocket*. Therefore they created a new design variant with three layers instead of two, as shown at the bottom of Fig. 8. The middle layer thickness was set to 200  $\mu\text{m}$  to enable through holes to be cut for housing the LEDs. The *Process Chain Selection Tool* was used to compare the design variants. Overall value was calculated as 0.70 for initial design, 0.89 when PMMA was used as opposed to PET and 0.90 for the design variant with three layers of PMMA. The  $\text{CO}_2$  laser was selected since the machining rate was greater than the excimer laser, improving both cost and production rate, whilst acceptable tolerance was maintained. Lamination was chosen over laser welding for the same reasons. Future work will develop product design optimisation algorithms that automatically identify and analyse large numbers of design variants.

The methodology successfully enabled detailed design and process chain selection by integrating expert process knowledge into the embodiment design stage. The designer was guided towards an optimal design for the hybrid manufacturing platform because they were:

- advised of manufacturing capabilities
- offered suggestions of design variants
- able to quantitatively analyse design variants



**Fig. 9** Design steps taken to create a “remove material volume” feature. Manufacturing information is retrieved from the *Hybrid Manufacturing Platform Model* in order to offer design guidance.

## 8 Discussion

The presented methodology enables optimisation of a design by integrating manufacturing knowledge into the embodiment design phase in a design for manufacture approach. This approach is particularly well-suited for hybrid manufacturing platforms because a designer is unlikely to have expertise in the widely varying technologies. The presented methodology included quantitative parameters to describe:

- product design details, to enable analysis of manufacturing requirements
- manufacturing capabilities, to enable identification of feasible process chains and offer guidance for design decisions
- product evaluation methods, to analyse the product value achieved by each process chain

The capabilities of the presented methodology and those reviewed in Section 2 are indicated in Table 3. Although many of the studies developed a formalised numerical framework, almost all were tailored to specific

processes or product feature types (e.g. volumetric geometries) and therefore are not suitable for the highly varied processes considered in the current study. The table also shows that many studies enabled a design to be evaluated. However, most required a detailed design to be input to the process; few supported the embodiment design process of generating a detailed design from a concept design. Of those that did, very few included a process chain selection procedure and these were all developed for specific technologies used in silicone-based MEMS products. The presented methodology is the only one capable of supporting process chain selection and embodiment design for a hybrid manufacturing platform. Conceptual design is out of scope for this study, but the process of translating a concept design into an initial detailed design is critical for hybrid manufacturing platforms, where the high level of process variation makes it difficult for a designer to have expertise of the full range of processes. The final row of the table indicates that several studies included more detailed simulations of the manufacturing process than in the present study. This enabled optimisation of factors such as the toolpath or processing temperature but the level of detail meant that such methodologies were strongly focussed on a specific technology and are therefore not suitable for a hybrid manufacturing platform with highly varied processes.

**Table 3** Aspects investigated in the present work and related studies

Aspect investigated	Reference number													THIS STUDY								
	[13]	[14]	[15]	[16]	[17]	[18]	[19]	[20]	[21]	[22]	[23]	[24]	[25]		[26]	[28]	[29]	[30]	[31]	[32]	[33]	
1. Integration of design and manufacturing data	●	●	●	●	●	●	●	●	○	●	●	●	●	●	●	●	●	●	●	●	●	●
1.a. Formalised mathematical knowledge-based methodology for design, process chain selection and evaluation	○	●		●	○	○	●	●	○			●		●	●	●		●	○	○		●
1.b. Formalised knowledge-based methodology applicable to hybrid manufacturing with highly varied processes		○																		○		●
1.c. Focus on enabling multidisciplinary collaboration	●	●	●																			
2. Product design evaluation and optimisation	●		○		●	●	●	●		○		●	●	●	●	○	●	○	○	●		●
2.a. Feature-based design method during initial embodiment design (or similar DfM support)			●				○	○							●			●	●	○		●
3. Process chain selection method			●	○	●	●			●	●	●	●	●	●			○	●	●			●
4. Computational manufacturing simulation/analysis (simulation, toolpath modelling, etc.)		●	○		●	○				●								○	○			
● = yes    ○ = partly/potentially    EMPTY = no																						

The presented methodology is particularly powerful in enabling a designer to create a feasible initial design without consultation with process experts. However, advice from process experts should be used to review the design and process chain before commissioning. The methodology cannot replace human expertise, but enables greater optimisation of the design and process chain for the same given time-input from process experts. Hence, the competitiveness of a hybrid manufacturing platform may be improved through employment of the presented methodology.

There are always uncertainties in design, manufacturing and evaluation activities. In some cases, these uncertainties are included in the methodology. For example tolerance requirements can be used during the design process to dictate acceptable manufacturing uncertainty. However, some aspects of manufacturing cannot be quantified but may be understood through human experience (e.g. unpredictable process traits, operator ergonomics). These must still be considered and therefore advice from process experts should be used to review the design and process chain before commissioning. Similarly, the translation of qualitative evaluation aspects into numerical evaluation parameters may introduce some errors so it is important to review the design with the customer and discuss which design parameters had the greatest impact on the evaluation of the product design rating. This allows the customer to confirm whether those critical design parameters can be varied or not. In some cases, the customer may prefer a quick turnaround but less optimised product design, in which case the time savings achieved through use of the methodology are hugely beneficial.

The implementation of the methodology developed in this paper depends strongly on the hybrid manufacturing platform it is applied to. The feature types offered to the designer in the design tool directly depend on the features that can be achieved by the technologies in a given platform. The hybrid manufacturing platform considered in this study is suited to products with a relatively flat profile due to inclusion of a polymer film lamination process. Due to the inclusion of aerosol jet printing, laser machining and micro-assembly capabilities, the platform is particularly adept for products with complex internal functionality, which present a challenge to traditional manufacturing approaches. Along with LED products, microfluidic devices are highly suitable. Products with a 3D external geometry are less likely to be manufacturable at a competitive rate because they are more effectively produced with alternative technologies. For a modular hardware approach, new processes can be added to broaden the range of potential products.

Recent trends towards modular and reconfigurable manufacturing are supported by the methodology. For a modular approach, the models in the methodology are created for a range of potential technologies. When a new technology module is introduced to a platform, the respective models become accessible by the tools for design and process chain selection. For reconfigurable manufacturing, the methodology could organise process technologies across several platforms to maximise overall productivity for the current products. Similarly, it could enable the optimal reconfiguration of process modules when unexpected disruption occurs (breakdown, material supply issues, etc.). A key extension that is currently being developed is to integrate physical control of manufacture processes into the methodology.

New hybrid manufacturing platform business models in which the owner of a platform does not require process expertise may be enabled by the methodology. A platform would be developed by an institution with expertise and then sold as a commercial package. The activities presented in this paper are well-suited to such business models. Activities related to platform initialisation are completed by the institution that develops the platform whereas those related to a specific product are completed by the institution using the platform. Due to the reduced involvement of process experts, it is critical that the design process is simplified to avoid product features that are difficult to manufacture. The presented methodology can achieve such simplifications. Similar business models already exist for single-process additive manufacture service providers, where potential customers use website-based simplified CAD programs.

## 9 Conclusion

This study presented a novel approach for design and process planning for hybrid manufacturing platforms. It is the first time a formalised methodology has been presented to integrate data for manufacturing, design and evaluation into procedures to support embodiment design, process chain selection and product design evaluation. While other studies have investigated these aspects individually, they are typically based on specific technologies or product feature types. No methodologies have been reported that can consider the wide range of process types present in state-of-the-art hybrid manufacturing platforms. A key novelty in our approach was to utilise commonality between highly varied manufacturing processes and product feature types. This enables optimisations of the product design and manufacturing routine that would not be possible without the methodology. The methodology was successfully validated by the complete design, process planning and product evaluation of an LED micro-device. The approach is of significant industrial importance because it enables new hybrid manufacturing platforms to be competitive with traditional manufacturing. It can also facilitate new business models and enable hybrid manufacturing platforms to take advantage of current trends towards modular and reconfigurable manufacturing.

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