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GRAPHICAL REPRESENTATION OF KEY ITERATIONS DURING THE DESIGN PROCESS

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ABSTRACT
A new design approach is proposed, which places the iterative nature of design at the heart of its structure. Design is modelled as a cyclical process, in which solution refinement is driven by information gathering and evaluation activities. This is intended to focus the attention of the designer on the quality and extent of the information that the design is derived from, as well as on the quality of the solution as it emerges. The application of this method, and the insight gained from it, is described using a case study example. A method of recording and then mapping the relationships between the key activities within this case study is then presented. This mapping allows a design activity, and the solutions emerging from it, to be analysed in the context of the understanding from which these solutions originated.

Keywords: Design process, iteration, methodology

1 INTRODUCTION
Commercial pressure for efficient design activities has led to a long tradition of design methodologies. Cross distinguishes between 'descriptive' and 'prescriptive' models of the design process [1]. The descriptive models, such as that by French [2], allow the design process to be more easily described, often by division into separate stages. The stages in the prescriptive models, such as Pahl & Beitz [3], are intended to encourage designers to adopt improved, systematic ways of working. The number of stages and terms used to describe them will vary depending upon the methodology in question. The design process is normally represented as starting with a market need, which is formalised into a specification. This is followed by phases of conceptual design, development (or embodiment) and finally by detailing.

In reality, the design process rarely follows a neat pattern of independent stages. Rather, a complex structure of overlapping and alternating activities is more common [4]. The sequential methodologies make a limited acknowledgement of this via the addition of feedback loops, allowing a return to earlier stages if required. However, this does not reflect the degree of iteration that is a widely accepted aspect of design, varying in scale from the cycles of a design optimisation algorithm to the use of market data by an automobile manufacturer to refine the design for the next model [5]. One cause of this design iteration is the quality of information available to the designer, which is not considered by many of the existing methodologies [6]. Instead they depend upon large quantities of data [7], rather than the iterative expansion of knowledge as the design is refined [8]. Evaluation of both the quality of information on which the design is based, and of the quality of the product being designed is neglected by the methodologies that are aimed principally at improving the design process itself [9].

There has not been widespread acceptance of these design process models in industry [10,6,7]. This is partly due to the fact that whilst many are based upon observations of what designers actually do in industry, this relevance is hidden by elaborate representation using abstract terms [7] leading to an apparent lack of correspondence between the models and the real experience of designers in practice [11]. The need to tailor design methods to each organisation, lack of perceived ownership as well as a lack of time to champion methods also contribute to the low acceptance in industry [10]. A further barrier to acceptance is that non-original design is most common in industry [6], and that designers already have a good intuitive appreciation of how to incrementally develop designs without formal structured methods [7]. Formal design models are only required when the designer meets a novel problem outside of his or her experience [10].

2 NEW CYCLICAL DESIGN APPROACH

A new approach for the design of novel products is proposed, which uses a cyclical structure in order to incorporate the iterative nature of design. Within each cycle, information gathering and evaluation activities drive solution refinement activities. It is suggested that all design activity falls within one of these three categories, and that they should each have equal weighting. This is a departure from the approach of the established methodologies, which deal mainly with solution refinement only, leading to solution driven results. This was considered important because the quality of any solution iteration is directly affected by the quality and extent of the information that led to it. The evaluation of the information gathered, and of any previous solution iterations, similarly affects the quality of the solution iteration. The proposed approach is shown pictorially in Figure 1.

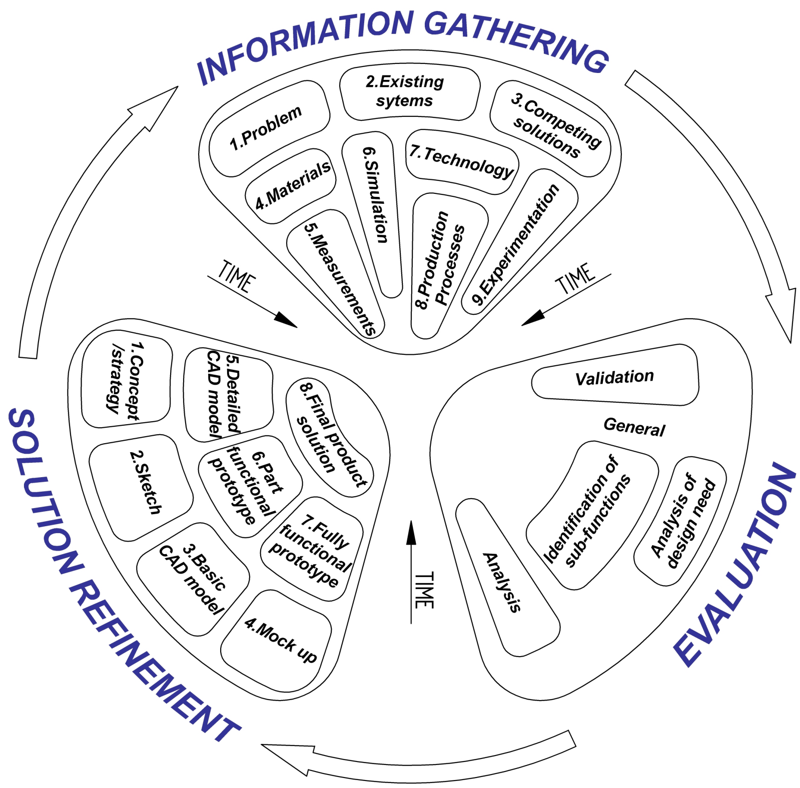


Figure 1. New Design Approach

An attempt has been made to retain the positive elements of the prescriptive methodologies within this iterative structure. In the information-gathering phase of the cycle, nine classes of information can typically be included, derived partly from the existing methods. The design process typically starts with the gathering of information about the problem that the design solution is intended to address and existing systems with which the solution needs to integrate. Competing solutions are considered an important topic for investigation, as they may be so successful that they negate the need for a new design solution. Alternatively they might have shortcomings that need to be addressed by any new design. Other key classes of information are materials and technology that might be utilised by any potential solution. It should be noted that any of this information may already be possessed by the designer and need not necessarily be new information. Potentially the most significant source of information during the design process is that generated by previous evaluation or solution iterations. An example of this might be experimental data generated from the testing of a previous solution prototype. These classes are intended to guide the designer to consider the amount of information that has been gathered in each of these key areas. However, the information required should not be considered to be limited to these classes and there is a potential for adapting the classes of information for particular applications or organisations. It is intended that this will encourage a feeling of ownership, addressing one of the issues with the existing methodologies.

It is important to note that, within the design process, all information is of little value until it is evaluated in relation to the specific problem, and its relevance to the design solution considered. It is imperative that as well as the information itself, the accuracy and scope of the information is evaluated. Similarly, a design solution cannot be refined without being evaluated. The form of this evaluation will vary depending on what is being analysed and the level of refinement achieved. Four categories have been included in Figure 1, although it is expected that the evaluation activities could be expanded into other areas. The four are validation, analysis, the identification of sub-functions and the identification of the design need.

Solution refinement is well covered by the existing methodologies. In order to measure the degree of solution refinement, progression towards a final solution has been broken down into nine stages. Starting with a concept or strategy (often referred to as a "black box" [12]), these stages are intended to classify solutions in varying stages of refinement, including sketches, CAD models and prototypes before a final design solution is reached. It is intended that this approach will lead the designer to the simplest testable solution, which can then be incrementally refined by adding functionality. This will reduce the amount of resources that might otherwise be committed to an unsuccessful solution iteration. As with the information gathering classes, the exact stages are open to adaptation for specific organisations and problems.

It is intended that this approach will not only more accurately describe design generally, but also allow a specific design process to be graphically represented, after recording the activities undertaken. This will address the issue of correspondence between the design model and real design activity discussed in section 1. During a literature search, no previous work on mapping the relationships between real design activities onto a design process model could be found, although the communications within an organisation have been mapped onto a design model [13], the time spent during iterations between design process stages [14] and the relationships between design decisions [15] have been mapped. The act of recording this data will also focus the designer on the areas of information and evaluation, hopefully leading to a greater understanding of both the problem and the solution. This model is deliberately simpler than previous models of design iteration (which focus mainly on iterations between different tasks during concurrent engineering [16,17]), in order that the process of recording data during design activity is as easy as possible (and therefore more likely to be done).

3 CASE STUDY – CERVICAL SMEAR IMAGING DEVICE

The application of this approach will be demonstrated using a case study example. This case study is based upon the IMI 'Objective Cervical Smear Verification System' project, GR/N30859. The aim of this project was to integrate recent advances in cell biology and image processing technologies to create an objective cervical smear test, using an automated approach. The core project team consisted of:

- Cell biologists with expertise in the production of antibodies used to label cell types
- Imaging specialists with particular expertise in x-ray imaging technology
- Academic engineers

Additionally, a wider group, including healthcare professionals and a project manager, supported the project. During this study, the proposed approach was followed. The activities conducted during the first ten design iterations are described below

3.1 Iteration 1

At the start of the project the engineers and imaging specialists had no prior knowledge about the application, other than that included in the project proposal. The project started by supplementing this information through site visits and a literature review of journal papers. This led to an increased understanding of the aims of the screening process, the practicalities of its implementation, and the causes of subjectivity in its results. Analysis of the processes involved identified the need for an inspection step to measure the sample adequacy, upon arrival at the screening laboratory.

3.2 Iteration 2

The insight gained during the first iteration formed an essential basis of understanding on which to build a successful solution to the design problem. However, it did not provide any information that would directly lead to the emergence of design concepts. Following the new approach, the evaluation of information from journal papers about existing automated screening systems led the project team to the conclusion that these systems retained the inherent subjectivity of the manual process. However, the liquid based sample preparation methods used appeared to be complimentary to the antibody technology, allowing the cells to be automatically imaged. This in turn led to the strategy of using coulter counters, although prior knowledge about this technology was limited.

3.3 Iteration 3

The emphasis of the new approach upon information gathering led to a more thorough investigation into coulter counters. Concern over issues of cleaning and the potential for cross contamination highlighted during a site visit led the engineers to adopt a strategy of containing the sample within a sealed, single-use, disposable device during processing. A sketch of the first concept, based on this strategy, is shown in Figure 2.

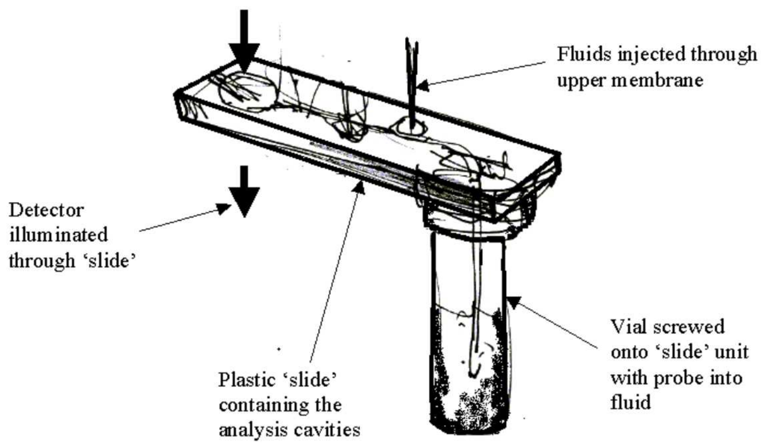


Figure 2. Sketch of device concept

3.4 Iteration 4

Information was gathered about the laboratory procedures to be replicated within the device, and the size of the cells in the smear samples. This led to the identification of the need to retain the cells, using a filter, and further information to be collected about these. A strategy of imaging the cells directly on this filter was investigated. After calculation of the number of cells that might be loaded onto the filter, the design and production of a simplest testable solution was possible. This prototype, made up of thin polycarbonate layers with machined channels, clamped around the filter, is shown in Figure 3.

Figure 3. First testable solution prototype

3.5 Iteration 5
The possession of a testable prototype allowed more information to be generated through experimentation. Evaluation of the fluid flow through channels of different geometries, the flatness of the membrane for imaging and the deposition of polymer beads (acting as model cells) provided an insight into the behaviour of the concept, and led to refinements in the design. This established sufficient confidence to allow greater investment in tooling for further iterations.

3.6 Iteration 6
Having gained a suitable basis of understanding about the features of the device and their behaviour, the next cycle examined how to package these features into a mass producible product. Feedback from stakeholders was gained using a series of mock-ups of the device. Analysis of the minimum number of parts was used in order to further refine the design solution, and reduce its cost.

3.7 Iteration 7
Before investment in injection moulding tooling, CAD models of the device were iteratively refined using information generated using an injection moulding simulation package, as well as models to investigate the sample flow through the channels. In order to reduce costs, this tooling, and the subsequent moulding of a small batch of parts, was produced in-house. Figure 4 shows a photo of one of the first devices assembled from injection moulded components.

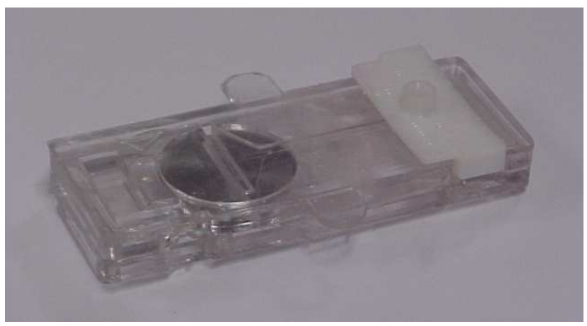


Figure 4. Early device assembled using injection moulded components

3.8 Iteration 8
The quality of the parts that were moulded was quite poor, partly due to the limitations of the machine that was used, and partly due to a lack of knowledge on the part of the designers about design for injection moulding. A significant problem was the removal of the parts from the mould. Analysis of the design led to the tooling surfaces being machined down in order to produce shallower parts. This gave a small improvement to the part quality and reduced the component cost.

3.9 Iteration 9
Further experimental information was collected from first hand production and assembly of the devices, as well as through testing using fluids to model the cervical samples. Evaluation of the devices performance led to a number of changes to their design, aimed primarily at easing the removal of the parts from the mould. These changes were again analysed using the moulding simulation software, before moulding a new batch of parts.

3.10 Iteration 10
Information about the performance of several alternative adhesives was gathered experimentally using a coloured dye introduced into the devices to highlight any leakages. The improved understanding between the fluid and adhesive interaction led to a notable reduction in fluid leakage.

3.11 Iteration 11
Polymer beads were used as model cells in order to generate information about the behaviour of particles within these improved devices. The number of beads that were counted in the devices was significantly lower than expected and the cell biologists blamed leakages within the device for the losses. The design was further refined, and it was decided to pay to have a batch of parts produced by

an injection moulding company. Figure 5 shows a photo of a device assembled using these outsourced components.

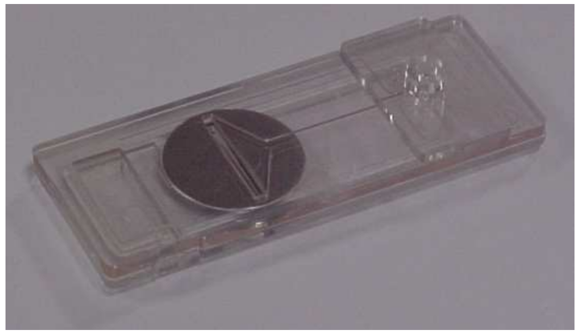


Figure 5. Device assembled using outsourced components

Experimental evaluation demonstrated, using a coloured dye, that the leaks were eliminated in the majority of devices. Having established sufficient confidence in the robustness of the devices, fifty smear samples were analysed using three different counting methods on each. The number of antibody labelled cells (as a proportion of the total cell population) was measured using a manual count of cells, an automated count of a larger number of cells on a microscope slide, and an automated count of cells within a device. These experiments validated the use of the devices. Following this, the research aspects of the project were handed over to the industrial partners for commercialisation of the design.

4 DESIGN PROCESS RECORDING METHOD

As described in Section 2, an important aspect of the proposed approach is the recording of the relationships between the key design activities, so that a graphical representation of them can be produced. This representation is intended to provide the designer with an improved insight into the activities conducted.

A spreadsheet template was produced, to be used for this recording method. On this spreadsheet, a description of each of the key information, evaluation and solution activities was entered, and each was numbered. The data recorded during the first five iterations is shown in Table 1. The information and solution activities were classified according to the classes shown in Figure 1, and the number of the corresponding class for each of these activities was also recorded on the spreadsheet.

In order to graphically represent the relationships between the activities, the number of the preceding activity also needs to be included. In Table 1, where the input of information is the result of previous evaluation or solution activities, the number of the information source is recorded in the column “IsourceE” (for information arising from evaluation events) or “IsourceS” (for information arising from solution events). This includes information arising directly from these events, for example experimental results from the testing of a prototype solution, as well as indirectly after the identification of a need for more information to be gathered. It should be noted that some information may be gathered directly as a result of following the new approach, and so some information activities may not be a direct result of previous activities.

The number of the information activity analysed during an evaluation activity is recorded in the column “EsourceI”. The column “EsourceI2” is also used if more than one information event is analysed simultaneously, for example when evaluating information about a new technology with respect to information about the application for which it might be used.

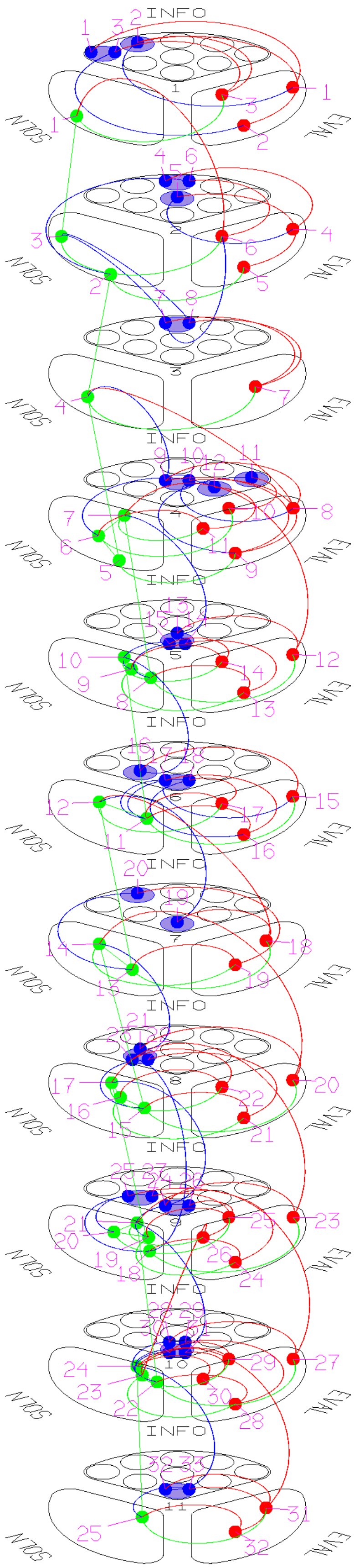
As described in Section 2, information itself cannot lead to refinements in the design solution unless evaluated, leading to an increased understanding. Solutions can therefore only be based upon an evaluation activity, the number of which is recorded in the column “SsourceE”. However, the solution may be a refinement of a previous iteration of the solution, in which case its number is recorded in the column “SsourceS”.

The activities recorded could all be considered as part of one continuous cycle containing micro iterations, or a large number of small cycles with one information, evaluation and/or solution iteration in each. However, for convenience, the activities have been grouped together based on their relevance to each other. For example, several micro iterations investigating alternative methods to achieve a particular function leading to a refined solution outcome, have been grouped together in one macro iteration. Similarly, several micro iterations investigating different competing solutions have also been grouped together. Importantly, these micro iterations were all conducted in sequence with no overlapping with other macro iterations. The number of the macro iteration is included in the first column of Table 1.

Table 1. Record of design activities during first five iterations of the case study

	Information gathering					*Evaluation*					*Solution focussing*				
	Info. number	*Description*	*IsourceE*	*IsourceS*	*Info class*	*Eval. number*	*Description*	*EsourceI*	*EsourceI2*	*EsourceS*	*Soln. number*	*Description*	*SsourceE*	*SsourceS*	*Soln class*
Iteration 1	1	Project proposal			1	1	Identified need for more process info	1							
	2	Screening laboratory visit	1		2	2	Process analysis - Need quality check	2							
	3	Screening process	2		1	3	Improved insight into need for objectivity	3	2		1	Strategy - Adequacy test	3		1
Iteration 2	4	Automated screening			3	4	Judged automated screening subjective	4							
	5	Liquid based cytology	4		7	5	Recognised could use with antibodies	5			2	Strategy - Use liquid sample	5		1
	6	Coulter Counters		2	3	6	Suggested use for adequacy test	7		1	3	Strategy - Coulter counter	6	1	1
Iteration 3	7	Coulter counters	6	3	3										
	8	Coulter Counter (visit)		3	3	7	Concern over cleaning issues	8	7		4	Sketch - Disposable device	7		2
Iteration 4	9	Antibody procedures		4	7	8	Identified need to retain cells	9		4					
	10	Filters	8		7	9	Selection of suitable filter type	10	9		5	Strategy; Image on filter	9	4	1
	11	Cell sizes	9		5	10	Analysis of cell sizes & filter area	11			6	CAD model of device geometry	10	5	3
	12	Manufacturing processes		6	8	11	Comparison of process costs	12		6	7	Prototype 1 - Milled layers	11	6	6
Iteration 5	13	Testing prototype 1		7	9	12	Identified filter needs clamping both sides	13		7	8	Proto.1 - Extra layer under filter	12	7	6
	14	Testing prototype 1		8	9	13	Analysis of filter flatness - need support	14		8	9	Proto.1 - support hole arrays	13	7	6
	15	Testing prototype 1		9	9	14	Evaluation of filter - need to tension	15		9	10	Proto.1 - Springs tension filter	14	7	6

A computer program was written to produce a diagram that would graphically represent the design activities conducted during the case study. This program reads the numerical data from the spreadsheet described above, storing the values in arrays. A series of frameworks, based on Figure 1, are first drawn, one for each macro iteration. Points representing the information, evaluation and solution activities for each iteration are then plotted within these frameworks. The relationships between these activities are represented using clockwise arcs. The resulting diagram is shown in Figure 6. A summary of the insight gained from following the approach for each iteration is included alongside the diagram.



1. Increased understanding of existing processes, and the causes of subjectivity in their results

2. Insight into shortfalls of competing solutions, and identification of liquid samples and coulter counter methods

3. Adoption of the strategy to contain the sample within a disposable device, based on concern of cleaning issues

4. Improved understanding of laboratory processes to be reproduced, and the production of a simplest testable solution

5. Experimental based understanding of the features of the device, leading to refinements in the design

6. Feedback on the acceptability of the packaging of the design features into an end product concept

7. Simulation based appreciation of the effect of feature geometry on suitability for production processes

8. Practical understanding of the injection moulding process leading to modifications to the tooling

9. Experimental analysis of the device performance using model cells, sufficient confidence established to enable investment in outsourced production

10. Experimental analysis of alternative adhesives leading to improved understanding of fluid interactions

11. Experimental validation of design concept using real biological samples

Figure 6. Graphical representation of the key case study design activities

5 DISCUSSION

Figure 6 clearly shows the relationships between information, evaluation and solution refinement activities conducted within the case study, and that the approach was followed. During the study, twenty-eight distinct solution iterations were observed, and it can be seen that, as predicted by the approach, each is derived from evaluation of information. This will be referred to as an I-E-S loop. Figure 7 shows the count of each solution class occurring per iteration. It can be seen that there is a general trend of increasing solution refinement throughout the design process, as expected. However, this is not a linear increase. The level of refinement remains fairly constant during the first four iterations, as the following of I-E-S loops increases the designers understanding of the problem. There is then a jump in solution refinement as the first testable prototype is produced. The level again remains constant as further information and hence understanding is derived using this prototype. The solution then oscillates as functional prototypes are tested, resulting in refinements to the CAD models that they are from which they are produced. It should be noted from Figure 7 that a "final product solution" was not reached during this case study, as it was based on a research level project. Had this class been reached however, this would not necessarily indicate an end to the design process, as further information may be generated and evaluated, and refinements to a solution could potentially reoccur in order to address issues such as manufacturing, distribution and marketing.

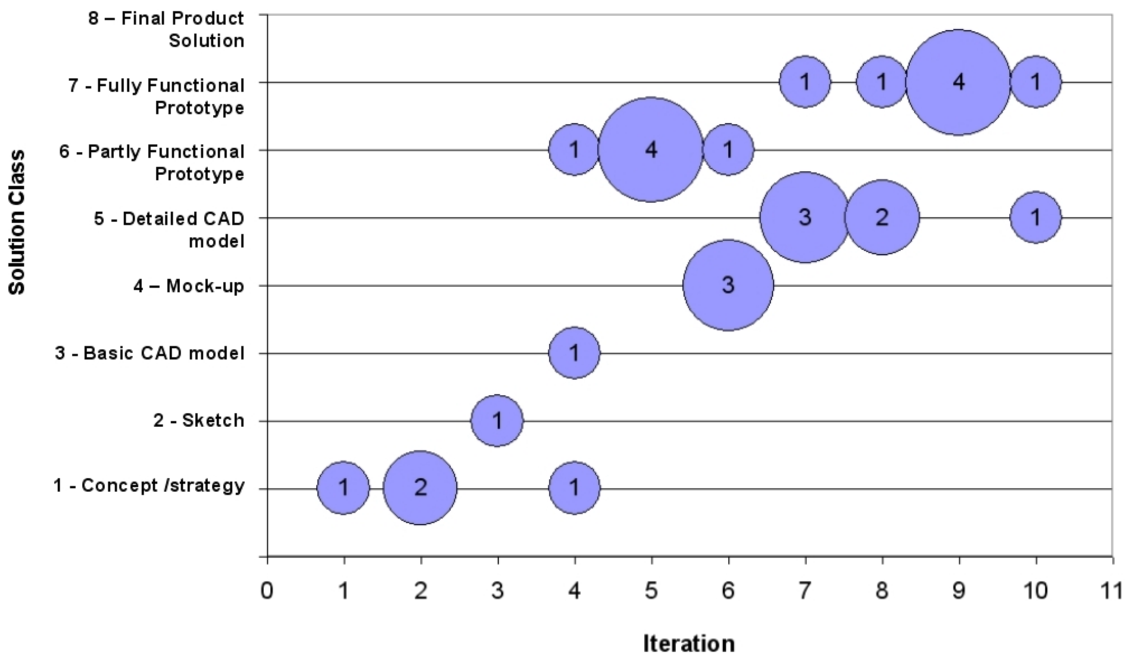


Figure 7. Count of solution class occurrence per design iteration

It should be noted that the number of information and evaluation activities is greater than the number of solution refinement activities. Evaluation of some information identified the need for the input of additional information rather than leading directly to changes in the solution. Information and evaluation that did not lead to a solution will be referred to as an I-E loop. It can be seen from Figure 6 that these I-E loops occurred early on in the design process (2 in the first iteration, 1 in each of the second, third and fourth iterations), before a testable solution had been produced. The diagram shows that the majority of information was either derived from, or gathered because of a previous evaluation or solution activity. The exception to this is information that came in the original project proposal (the "design brief"), and that which was gathered about competing solutions, following the approach. As well as these new starts, it would be expected that there were several "dead ends" reached during the process. However, each solution was evaluated, and if this indicated that the particular solution should be abandoned, a new solution typically still arose. This new solution would be based on an earlier solution rather than the previous, abandoned one, and this is most clearly highlighted during iteration 5, when there are three solutions each based on a solution from the previous iteration.

An important aspect of consideration is the type of information that each solution is primarily based upon. As stated above, each solution is derived from evaluation of information, but the class of information at the start of this I-E-S loop may be useful, particularly for any retrospective analysis of a design process in terms of the quality of the solution output. Figure 8 shows the count of each solution class resulting from each information class.

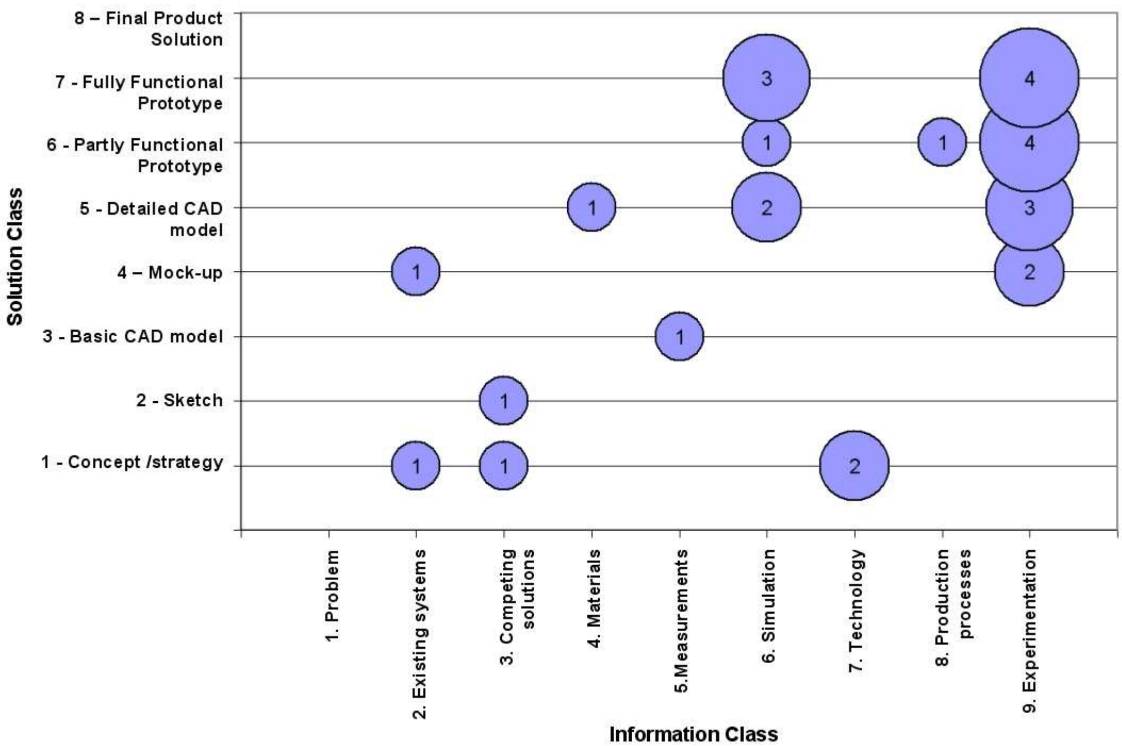


Figure 8. Count of Solution classes derived from each Information class

It can be seen that experimental data drove the most solution iterations, and that these varied in refinement from mock ups to fully functional prototypes. As lean approaches are increasingly applied to all organisational operations [18], pressures to reduce product development time may mean that the number of design iteration cycles is considered. The need for these solution iterations, based on experimental analysis of previous prototypes, may be called into question. The use of this mapping approach allows the cause of each iteration to be identified. In the case of this case study, it can be seen that they led to an improved understanding of the device features (during iteration 5), and improved understanding of the injection moulding process (iterations 8 and 9). In hindsight it could be argued that this understanding, particularly in the case of the production processes, should have been in place before the design activity started. Alternatively, an additional member of the project team could have been introduced with expertise in this area. This would have led to a shorter design development time, with a more linear increase in design refinement in Figure 7. However, in this particular project considering the design of a novel product, the project team was established before the production methods had been defined. It is important to note that given this situation, the use of the design approach allowed this understanding to be developed as needed. Also, every iteration cycle provided additional insight into the design problem and solution. It is impossible to say whether elimination of any of these cycles would have been possible whilst still retaining this insight. The amount of resources invested in each activity is not recorded by this approach. The approach used is intended to generate a large number of small, testable solution iterations, with minimum investment in each until sufficient understanding is attained. This process builds confidence in the performance of the solutions, reducing the amount of cost that might be committed to unsuccessful solutions.

CONCLUSIONS

In this paper a new design approach has been proposed, which is intended to provide the designer with an evolving understanding of the problem, leading to the generation and refinement of design solutions. This has been illustrated through the use of a real case study example. This approach was then used as the basis of a method of recording and mapping the design activities during the case study. This mapping allowed the design activity, and the solutions resulting from it, to be analysed in the context of the understanding from which those solutions originated.

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