INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED'09
24 - 27 AUGUST 2009, STANFORD UNIVERSITY, STANFORD, CA, USA

AN INTELLIGENT DESIGN ENVIRONMENT – OVERCOMING FUNDAMENTAL BARRIERS TO REALISING A STEP CHANGE IN DESIGN PERFORMANCE AND INNOVATION?

Ben Hicks[1], Hamish McAlpine[1], Eric Blanco[2], Marco Cantamessa[3], Francesca Montagna[3], Mario Storga[4] and Peter Törlind[5]
(1) University of Bath, UK (2) Grenoble Institute of Technology, FR (3) Politecnico de Torino, IT (4) University of Zagreb, HR (5) Luleå University of Technology, SE.

ABSTRACT
In the modern design environment, demands on performance, innovation and productivity are always increasing as global competition rises and business models(such as the product-service paradigm) evolve. Central to the ability of organisations to realise continued improvements has been the widespread adoption of new design tools, methods, technologies and processes. Arguably, today's highly distributed design teams are almost totally reliant on these elements to be successful. Whilst there is no doubt that they have improved performance in many cases, the sheer number and variety have given rise to new issues, such as *information overload* and *analysis paralysis*. This paper argues that one way to significantly improve this situation is via an 'intelligent design environment' in which the tools, methods, technologies and processes are *active* components that - where appropriate - *intervene* in the design activity. A network of design research groups have held workshops to theorise about possible active elements and their interventions. The results, consisting of an overview of possible active elements and interventions, fundamental research and technical challenges, and the possible benefits are discussed.

Keywords: teams, tools, technologies, process, performance, environment

1 INTRODUCTION
Realising improvements in design performance lies at the heart of the international research effort and is one of the primary motivations for the development of a design science. In more general terms, improving design performance can be considered to involve minimising the time and cost of the design process while maximising the quality, performance and function of the product [1][2]. Intrinsically related to these high level goals are a multitude of complex factors concerning creativity, innovation, collaboration and communication, CAE tools, information and knowledge management, process management and decision-making. Aspects of these dimensions have been addressed by research groups around the world and include design rationale capture [3], improved management of design information and knowledge [4], design discourse [5], design review meetings [6], collaboration [7], decision support, and traceability in design [8] [9] [10].
In general, much of this research effort has either provided the basis for - or resulted in - the creation of new tools, methods, technologies and processes, many of which are made available to the practitioner through consultancy and knowledge transfer activities, publication, distribution by software vendors, open-source code and freeware, or are encapsulated in other technologies. This wide variety of tools, methods, technologies and processes continues to expand, driven by the needs – real or perceived - of design practitioners, advances in information and communication technologies, advances in science, and changes in the nature of the design activity and designed artefact itself, such as the product-service paradigm [11].
Whilst there is no doubt that many of the tools, methods, technologies and processes have and will benefit design practice, their existence and continued development gives rise to a number of general concerns:

- Firstly, as the number of new tools, methods, technologies and processes increases, so too does the challenge of effectively selecting, implementing and managing them to best support the given design task (sometimes referred to as dissemination and implementation). This includes questions such as *What to use?* and *When to use it?* Tools and methodologies have potential validity and can conveniently be used in some situations, but not always, since they could lead to an inefficient process or even to flawed conclusions. For example, sometimes a tool has to be excluded *a priori*; sometimes it can be used, but only after a context analysis that defines its applicability conditions. The directions for use differ in relation to situations. The focus on context in many disciplines [12] and in-particular in some approaches to design [13] provide emphasis on modelling and use of contexts. Each situation might therefore lead to a sequence of different technical actions that can be translated into an integration of different tools.
- Secondly, new tools, methods, technologies and processes do not necessarily replace existing ones or improve efficiency from the outset and as a result can demand increased resources both in terms of the designers time and cognitive load – *How can they be used in a complementary manner?* The issues surrounding the plethora of new and emerging tools and methods has been researched by [14], who highlight tool overload as an emerging issue. It is also arguable that the increasing variety, diversity and number of tools, methods, technologies and processes contribute to information overload [15] and 'paralysis by analysis' [16].
- Thirdly, the creation of new tools, methods, technologies and processes necessarily demands that the designer and design team be proficient in their use - in order to avoid errors in their application and costly inefficiencies. The pace of development of such tools and the diversity of the user base means that training requirements are often complex and their effectiveness can be hard to evaluate. Frequently, organisations have access to tools and methods that have been costly to implement, but in reality are rarely used in product development. They are often regarded as an annoyance because the gains in productivity are often only realised through extensive training.

All of these factors mean that many tools, methods technologies and processes are not adopted, or those that are will only be partly implemented, ill-understood or inappropriately used. As a consequence, there is increasing concern about the impact of new tools and technologies on design performance and in particular *creativity, innovation, fundamental understanding* and *productivity* [17]. In this earlier work it was argued that some of these issues (and in particular those concerning the evaluation of the practices and needs of industry) could be addressed through the use of an 'intelligent design observatory'. Here the term intelligent was used to refer to the automated capture, structuring, organisation and analysis of all aspects of the design activity. To begin address these issues, an international Design Observation Network (named iCORE) was formed, involving research teams at the University of Bath [17], Grenoble INPG lab [6], Luleå University of Technology [18], University of Zagreb [4], Turin [9] and Stanford University [19].

To date, the consortium have been considering the issues surrounding holistic observation of distributed design teams, the technologies required, and robust methodologies for conducting design experiments, all of which are essential for establishing core data that underpins research activities and ultimately design science. However, at a workshop in December 2008, the network was challenged by industrial partners to consider how the technology capability and methods associated with intelligent design observation could be used to deliver more immediate and tangible benefits for the design team during a particular design episode. An alternative way of interpreting this question within the context of the previously defined issues is:

"How can design observation overcome the problems associated with information overload, technology and tool overload, and maximise the benefit of the tools, methods, technologies and processes for a given design episode?"

Clearly, observation itself can provide a better understating of design practice which can in turn be used to provide training and feedback to the design team. However, much of this would necessarily be undertaken after the design episode, which is not consistent with the requirement to provide benefits within a particular design episode. In order to answer this challenge, the intelligent design observatory as described by [20] would need to be extended from a passive observational environment into an 'active' one. Here the term 'active' is used to denote active support and intervention (by virtue of

intelligent tools, methods, technologies and processes) made within a time-scale that has an effect on the outcome of the design activity. An important distinction here is that the intervention is made automatically by the intelligent tool rather than by external observer. Within the context of design, active support and intervention could include, for example, automatically 'pushing' relevant images of potential solutions from a previous project, displaying the cohesion levels of the team, or ensuring documents are dynamically ordered such that relevant information is always to hand. It is proposed that such 'intelligence' could arguably offer major benefits to the design team in terms of performance by both freeing the designers' time and removing error-prone routine tasks.
This concept of intelligent support (active tools, methods and interventions) can arguably be extended across the various dimensions of design - including the physical environment, the team, tools, technologies and management. This is illustrated in Figure 1, below.

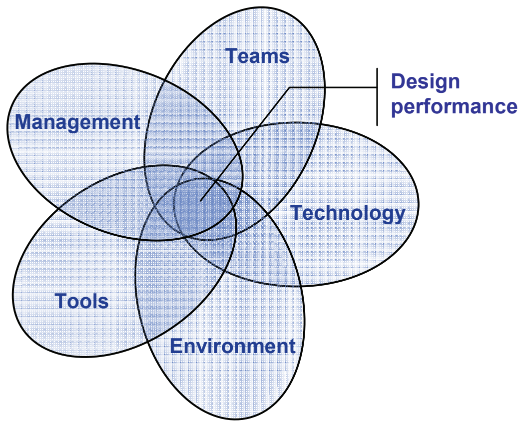

Figure 1. Five interrelated dimensions of design

Prior to exploring the potential range of possible active elements and their interventions, the process of intervention is first considered in more detail.

1.1 A process model for active support and intervention

Whilst the aforementioned examples of possible active support and intervention may appear to be trivial, the process of defining and delivering an intelligent intervention is anything but. In particular, it is first necessary to consider *What the purpose of the intervention might be? When it will be made? What it will include* and *How it will be made?* In more general terms, an intervention can be considered to involve the five phases shown in Figure 2 and explained below:

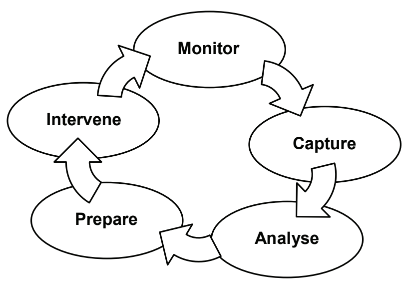

Figure 2. The five phases of active support and intervention

1. **Monitor** the activities and interactions of the design team. Including information, communication and tools.
2. **Capture** the inputs, outputs, content and relationships between activities and interactions.

3. **Analyse** the activities, interactions and content to determine whether an intervention should be made.
4. **Prepare** the intervention including its form (medium, amount, format) and recipients.
5. **Deliver** the intervention by virtue of an appropriate technical means.

1.2 Active support and intervention in design

When considering the various definitions of design [21] and design processes [1, 2] it is clear that the theoretical space of all possible interventions within the context of design is potentially vast. However, in practice the space of possible *beneficial* interventions will be constrained by current design thinking, the nature of design practice and technological capability. Hence these constraints will ultimately dictate the level of intelligent support that is possible and in turn the magnitude of possible improvement in design performance. Notwithstanding this, it is the underlying proposition of this paper that an intelligent design environment based on active support and intervention offers a means to realising a step change in design performance and innovation not seen since the advent of CAD systems. In order to explore this hypothesis further and to provide an insight into the feasibility of an intelligent design environment, a constrained space of interventions are explored in detail. This constrained space is depicted in Figure 3 and includes what can be thought of as the four core interrelated activities of design:

1 **Problem-solving** – problem formulation, goals, convergence and divergence.
2 **Decision making** – Alternative evaluation and choice, action choice and control, design rationale and collective decisions [22].
3 **Collaboration** – communication and sharing of information between individuals and teams [23].
4 **Information transformation** – the consumption and generation of information during the design process [24].

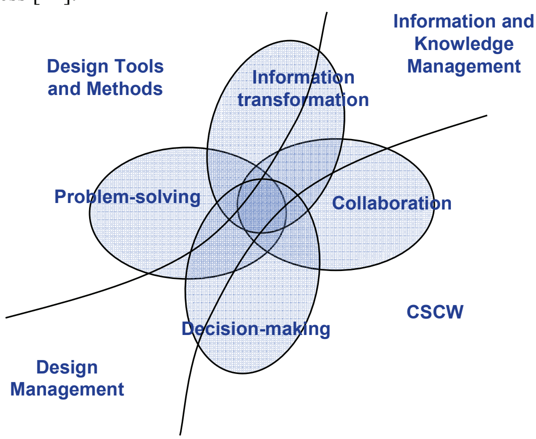

Figure 3. The core activities of design

In order to explore the various forms of active support and intervention across these four areas, a number of workshops have been held involving the research laboratories of the Design Observation Network. For the purpose of presenting the results, each of the four areas of problem-solving, decision-making, collaboration and information transformation are discussed in turn. In particular, each section considers current design thinking in that area, along with tools and methods in order to explore requirements for – and the benefits of – active support and intervention.

2 INTERVENTION DURING PROBLEM-SOLVING

Where problem-solving is considered there are arguably two important stages; divergence and convergence. With this in mind, interventions based on stimulus and cohesion could arguably offer significant benefit.

2.1 Context based stimuli in creative sessions

One frequently-used method in brainstorming is using random stimuli [25]. By capturing and analyzing the turn taking and pauses in a creative session (how active the designers are) intervention could be made when the activity reaches a certain threshold and provide the team with additional stimuli (random selected images, objects or a nouns). The stimuli can also be based on the previously created design history - bringing up design sketches, images and websites from the Internet using 'triggers' (based on turn taking, questions, documentation) captured from the current design session. An example of this is work by [26], where both sketches and drawings from past projects and related images were revealed to the design team to encourage divergence and innovation.

2.2 Cohesion and shared understanding

During group activities and in particular those associated with problem-solving, there is a need to ensure team cohesion [5] and what is more widely referred to as shared understanding. Significant progress [5] has made in the analysis of design discourse and the emerging methods enable discourse to be assessed and the level of shared understanding to be extrapolated. Presently, these methods are limited to retrospective analysis of design episodes. If their applicability could be extended to near real-time analysis then interventions could be made when a lack of shared understanding is identified. Furthermore, it would be possible to identify members of the team who were trailing others and remedial action could be suggested.

3 INTERVENTION DURING DECISION-MAKING

Within the product development process, it is possible to identify critical points at which one must support a decision, typically by applying a method or tool. Such decisions can be related to the artefact being designed, to the process to be followed, or to the resources to be involved. For the purpose of decision-making, it would be desirable for active support and intervention on three different levels: (1) by supporting alternative evaluation and choice by tracing design changes, (2) by supporting planning and control activities in the design process or defining a rationale in the design processes (3) by supporting collective decision-making.

3.1 Tracing design changes

Design changes can have a negative impact on the design process in terms of technological influence and costs. After changes are implemented, it is difficult to recreate the decision-making process, with much of the supporting documentation – both formal and informal/personal in nature scattered throughout the extended enterprise. Moreover, central to the ability to capture, analyse and prepare an intervention is the need to understand the relationships between the information needed, and that generated with the existing information. One means to achieve this might be through the creation of tools for semantic analysis, and indexing and structuring of information to support the tracing of design changes.

3.2 Activity planning and control

In activity planning and control, two possible interventions have to be taken into account. From a top-down perspective, any design process will to some extent have to adhere to a given plan, or formalised process, involving meetings, deliverables, activities and milestones. The creation of related documentation and the monitoring of project progress is currently a time-consuming and error-prone task. Hence there is a requirement to provide a means for automating activities of this kind, reducing the amount of work, and improving the quality of the documentation and its adherence to the actual results of the project. From a bottom-up perspective, "purposes for action" often arise from within the process itself, in ways that usually cannot be part of a predefined plan or development process. Examples include the tracking of alternative solutions when explored in parallel, the tracking of consequences of engineering changes, and making sure that modification proposals are duly followed and lead to actual decisions by the design team. Hence, interventions could have the objective of providing a method for monitoring "emergent" problems and related actions and for correctly relating them to the formalised part of the design process, which is generally supported by workflow and project management tools embedded in PLM frameworks. If there were support for tracing and analysing not only the problems but also related decisions, it would be possible to identify their rationale too. In order to achieve this, the uncertainties from a decisional point of view, the information needed to make any decision and the relationships between decision-makers must be identified. These elements can allow the reuse of lessons learned arising from past experience and the definition of information re-use scenarios. Following the structure presented in Figure 2, semantic technologies are required to capture and analyze all these information elements, and tools that are able to contextualize the information are needed for preparing and delivering information in design activities. Handling all the information stemming from the complex activities and information flow in a design meeting requires state-of-the-art information management methodologies. In particular, semantic elaboration technologies will be adopted within the intervention to help three crucial steps: identification of context, extraction of conceptual information, and storage and search. Semantic elaboration, mainly at the linguistic level, could also be adopted to extract conceptual information from meeting sentences and/or documents. This will allow indexing of the meeting transcript and technical document according to their semantic content. To prepare and deliver the intervention, Multiple Criteria Decision Analysis (MCDA) methods [27] could be used to "help decision makers learn about the problem situation, through organisation, synthesis and appropriate presentation on the information to guide them in identifying a preferred course of action" [28]. In particular, value or decisional trees could be used to prepare and deliver possible actions and feasible scenario alternatives [29].

3.3 Collective decision-making

Finally, designers participate in collective decision-making process that can be supported by intervention from tools and methods. In this case, the decisional context could be analysed in terms of the actors involved in the decisional processes, their knowledge domains and their different objectives. Methods for the identification of actor's action spaces and roles [30] could be used and tools and methodologies for modelling the decisional environment [31] can be used to trace decision making processes [32]. The different contexts (participant role, organisational role, decision making context, location and time, etc.) need to be taken into account and for this, the adoption of semantic modelling techniques – based on encoded ontologies that have the advantage of generality and customisation with respect to the project context – could be very useful.

4 INTERVENTION DURING COLLABORATION

Here, the focus on possible interventions will be for distributed collaboration, although the interventions could also be delivered to co-located teams. In distributed collaboration, a very common problem is the lack of communication between the team members and difficulty in creating a common understanding [33, 34]. When working in a co-located setting, the informal day-to-day communication between team members is used to rapidly exchange contextual information, which results in more awareness of people, knowledge and process and also helps in creating a shared understanding. This is largely absent in distributed situations. These problems are compounded as the window of opportunity for synchronous communication can be limited due to the different time zones [35]. These aspects give rise to a number of areas for active support, namely 1) re-experiencing remote team activities, 2) collaborative objects and 3) assessment of collaboration. These are discussed in turn below.

4.1 Re-experience

Where distributed teams are considered, there is a need to provide teams with a higher awareness of the current state of the product/process through, for example, sharing a brief synopsis of the remote teams' efforts. This could be done by visualising artefacts created by the remote team (sketches, CAD-models and other design records) and generating a synopsis that will act as a bridged memory space. The goal is to provide the team members a brief synopsis of the most important parts and to re-experience the dynamism and richness of the work in the remote team. The support for *Re-experience* could be based on the collective knowledge stored from the remote teams meetings and other interactions. Today, technology exists to store meeting information (video, audio, meeting notes, presentation slides, etc) [36] as well as personal information such as that contained in less formal records such as the designers logbook [37]. Using this existing technology, the meeting can be replayed as an intervention in future design sessions, although the user is still likely to have difficulties in finding relevant parts of the meeting. Jaimes et al. [38] describe the problem as *"If everything is stored, how do I find the piece of information I am looking for, particularly if I do not remember the exact details needed for retrieval?*

By using more sophisticated automatic indexing of meetings (identifying active speakers, differentiating between different types of tasks, transcribing the discussion, etc.) relevant part of previous engineering meetings could be re-experienced in a much more efficient and timely manner.

4.2 Collaborative objects

The research on design activities show that design is supported by a wealth of 'intermediary objects' [39]. The problem is that these objects often have multiple roles. Some support representations of decision, whilst others support cognitive synchronisation. One potentially beneficial mode of support might be to support the intelligent capture of these collaborative objects and the context in which they were used [39]. It is particularly important in this case to provide contextual elements which give sense to collaborative objects during future re-use. Such capability necessitates the creation of an activity model of the design team that is linked to the type of objects that are used by the stakeholders. Through observation, it is possible to highlight the critical phases in, for example, a meeting (e.g. a convergence and production period), which includes or reflects key decisions of the meeting [40]. Relevant intermediary objects can therefore be identified along the critical phases and basic indicators could be elaborated based on the time of object use or collective engagement around the object. These could also be used to identify those objects that are relevant to keep from a design rationale perspective. If it were possible to identify and classify activity patterns that can be observed or emphasised through intermediary object production and use, then information re-use could be intelligently delivered through accessing the object, rather than traditional Management Information Systems.

4.3 Assessment of collaboration

Increased digital mediation in engineering design affords greater tracking of a designer's activity when using design tools. Such tracking technologies already allow key events to be identified and activity patterns recognised - based on case reasoning or context analysis. Extending this to monitor the collaborative process in real time, it may be possible to 'push' contextualised best practice to designers, measure the degree of collaboration, and to qualify the contribution of a particular designer. This type of intervention could be used to foster collaboration, identify a lack of collaboration and intervene accordingly.

5 INTERVENTION DURING INFORMATION TRANSFORMATION

In the area of information transformation, interventions concern 1) the access of existing information, 2) the traceability of the development of information and 3) processes utilised in generating information. Possible useful interventions in these three areas are discussed below.

5.1 Information access

The design process is heavily dependent upon information provision – the right information, in the right amount, in the right place, at the right time [41]. This is illustrated by the fact that designers can spend up to 150 hours a year searching for information [42] much of which can be spent composing search queries, refining searches and screening documents. Within the context of active support and intervention, issues surrounding information access could be addressed through active information management systems that automatically respond to the activities and tasks of the design team. For example, previously developed techniques such as Non-zero match searching and faceted classifications [43] could be extended to dynamically organize existing documents according to the activities of the designer, such as those described by [44] and the emergent product architecture using, for example, frameworks such as DEDAL [45]. Clearly a prerequisite for such an intelligent information management system is the need to capture activities from both verbal and written sources in order to identify patterns and reorganise documents such that the most relevant are to hand.

5.2 Traceability of the development of information

The shift in emphasis from product delivery to product-service delivery means that the 'provider' becomes both more intimately concerned with the product over its life-cycle and involved with the product over a longer time span. This in turn requires that engineering design information (EDI) development must remain traceable (so that the EDI is made more accessible, understandable and reusable) throughout the decades that a product remains in service. Based on previous research results

[46-48] it is argued that such traceability is required because without it the trustworthiness, understandability and appropriate re-use of the information cannot be guaranteed at the point of use.
In order to understand and re-use existing EDI, contextual information concerning meaning, reasons, arguments, documentation, choices, consequences, etc. is required. This itself requires advanced EDI traceability methods, models and tools. These are currently lacking, with support for EDI traceability hampered by the lack of methods and tools for 'capturing' and documenting useful aspects of the development of engineering design information. The current engineering design environments frequently militate against traceability through exchange of engineering information across corporate and discipline boundaries, re-use of existing information in new and unpredictable contexts and transposing information from one format to another, inevitably losing some in the process. Furthermore, because of a lack of formal representations of the complex engineering design information, these exchanges still occur 'informally' (i.e. outside of structured information management systems) much of the time. As a consequence, retrieval of the engineering design information objects (e.g. with respect to format, type, and contents) as well as correct interpretation of its content (due to the specific domain context) is often significantly hindered.
Some of these issues could be addressed through active support and intervention which monitors and captures the following elements:

- Purpose determination (defined in terms of what traceability should do) – the capacity of the traceability method to conform to the project development scope, role of the engineering design information and the product development, legal, quality and other key requirements of the organisation.
- Solution proposal (defined in terms of how traceability is achieved) – the capacity to trace development from one representation to another, based on given semantic relations between them and constrained by existing tools for supporting everyday engineering working practice.
- Information content recognition (emphasizing a traceable engineering design information record) – the capacity to link between different levels of product/design abstraction such as requirements, functions, detail description, as well as description of the activities, events and resources involved in the engineering design process.

It is clear that if it were possible to capture and identify these elements, support could be provided to both improve traceability during information transformation, as well as to highlight elements such as information loss [49] and information quality [50] during, for example, decision-making and problem solving.

5.3 Information generation processes

As previously stated satisfying the information needs of designers and improving information access are two important areas of research. Two means for achieving this are methods of information 'push' [51] and workflow models respectively. Within the context of active support these two related approaches could be implemented to capture the activities of designers, and in particular their use of tools such as the Internet, in order to record the information generation processes and also profile their information needs. The former could be used to underpin workflow models and also support traceability (5.2), while the latter could be used as the basis to predict information needs and 'push' potentially useful information to the designer. The challenges for this involve primarily the technical challenges of monitoring user activity, profiling information needs and recognizing design patterns.

6 DISCUSSION

As previously stated, the theoretical space of active support and intervention is potentially vast and the previous sections represent only a small subset of potentially beneficial situations. The purpose of this paper is not to exhaustively identify all possible interventions or identify the interventions that might be the most beneficial, rather it is to theorise about the range of possible interventions and elicit some understanding of the research and technical challenges inherent for their realisation and Intelligent Design Environment (IDE). In order to support this, the key elements of the previous discussions are now used as the conceptual basis of a vision demonstrator for an IDE.

6.1 An Intelligent Design Environment – vision demonstrator

For the purposes of illustrating the capabilities of an IDE and exploring how the interventions discussed previously could benefit engineers in practice, a hypothetical but relatively common design scenario is considered: Imagine a distributed design team involving three locations and around 30 members, who are working together on a 24 month project concerning the design of a large machine system. The project involves a significant element of new design work. They hold regular design review meetings and quarterly client review meetings. In the past, the organisations involved have experienced a large number of problems when undertaking distributed projects of this kind. However, for this project the team have been using an Intelligent Design Environment that incorporates the active support and intervention capability described in sections 2 to 5. When asked about the benefits of the environment the responses included:

- **Chief Engineer: "**When we are undertaking creative sessions such as brainstorming, we see a real-time representation of the cohesion between the team members. This has really helped us to identify areas where there is a lack of shared understanding, but also where there are opportunities for divergence. In addition, there is an interactive wall which displays images from past projects and also the Internet which update to reflect the topic of discussions – this has helped us to be more divergent as well as allowing us to re-use existing designs more frequently. Sometimes we feel as if the IDE is one-step ahead of us!"
- **Project Manager:** "Every month we hold Design Review Meetings, during which a huge number of documents, models and artefacts are presented by the teams. Sometimes these can go on for hours and usually relate to the previous meetings. In the past, we have wasted a lot of time just finding information and revisiting decisions. With the IDE we can see the decision-making processes from previous meetings and all the relevant information (documents, CAD models etc.) is always to hand."
- **Project Co-ordinator:** "Many of our team members also work on other projects and spend a proportion of their time away from the project. In the past it has been really difficult to bring these individuals back 'up to speed'. However, the environment has an ability to automatically generate synopses of work from different periods that highlight all the key activities, decisions and rationale. So, in a matter of half an hour they can be brought right up-to-date with progress without the need for meetings, which are often hard to arrange because our team is international."
- **Senior Engineer:** "One of the key factors in our competitiveness as a team is our ability to re-use existing designs. However these invariably need some modifications. Central to undertaking these modifications is access to existing design records. When working in the IDE, these records are automatically 'pushed' to the designer, which when it first happened was a bit disconcerting – how did it know I needed the documentation? Could I trust it? I quickly saw the benefits though: Even once you have the documents, it can be very difficult to extract the necessary information. However, the IDE provides the ability to retrace the development of the document and this really aids in the process of understanding. It also means I know I can trust what it provides."
- **Technical Director:** "We hold regular meetings with our clients to report the project status, key decisions and milestones reached. Inevitably the clients will ask questions that I hadn't anticipated, relating to decisions, the rationale behind them and why we didn't go with certain alternatives. In the past this has been difficult to answer and I often had to admit "I don't know", but now we can give them the answer on the spot."

6.2 The key research and technical barriers

Through consideration of the elements of active support and intervention, and the hypothetical scenario presented above, it is possible to identify a number of common research and technical barriers to the creation of an Intelligent Design Environment. These common elements are summarised under the five phases of active support and intervention.

Monitoring

Given the breadth of the possible interventions, it is evident that a wide variety of dimensions need to be monitored. These include the activities of each member of the team and their interactions with systems and objects. Furthermore, there is also a requirement to monitor paths to objects, such a search paths and related information which - as identified in many of the previous examples of intervention – is necessary to provide the context. This breadth and depth of dimensions will necessarily require a large multi-modal sensory system capable of monitoring individuals, information handling activities, discourse, interactions with tools, technologies and physical objects.

Capture
There is evidently a major challenge concerning the dimension of capture and storage. In particular, there is a requirement to structure and arrange massive amounts of multi-modal information (video, audio, documents, CAD-models) and create relations between them. For example, a one hour design episode can generate Gigabytes of data, which if scaled over a 12 month design project with large teams would be almost impossible – or at least prohibitively expensive - to manage. Furthermore, there is a requirement to capture informal communications, and communication outside the environment. Finally, with such extensive information capture – including the activities of identifiable individuals - the issues of trust and privacy are likely to be a concern. For example*, which information is stored? Who can access the stored information? For how long is the information available?*

Analyse
Central to the ability to analyse design and thus determine whether an intervention should be made is the need for a theoretical model of activity, such that events and stages of the design episode can be identified and design patterns recognised. This includes both the activities of the designer and the collective design episode and particular tasks. The latter of these is at a macro level (aggregated) and the former at a micro level. Furthermore, the level of aggregation will clearly have implications for capture and storage. In addition to the need to develop a sound theoretical basis for design activities, a prerequisite for almost all active support and intervention is the need for contextual information and the ability to semantically analyse the information. It is clear that these two elements of context and semantic (content) analysis are major research and technical barriers.

Prepare
Few of the aforementioned intervention scenarios require the preparation of representations beyond that of the tool, system or medium being considered, e.g. pushing a CAD model to a designer undertaking a CAD activity. However, it may be the case that interventions can be prepared for media that are not the focus of the current activities. For example the Lulea Collabatory [7, 18] has a colour changing wall that could be made to vary according to the performance of a current activity. With this in mind, how can we create an "intelligent" design environment that will not annoy or distract as much as the infamous Microsoft Office 'paperclip' assistant? 'Calm' and 'ambient' technologies [52] are not new and there is a growing awareness of their benefits, but the guidelines for, and philosophy behind, their creation are at present more from the artistic realm than the scientific.

Intervene
A prerequisite for intervention - and ensuring that those interventions are beneficial - is the need for a performance model of the design activity. This model would enable a switch from a descriptive perspective of design research on design activity to the development of a prescriptive approach that tends to increase design performance. Deciding when to intervene is a key research challenge and one that may need to be approached in an iterative manner in parallel with the development of technology that underpins the components of an Intelligent Design Environment.

7 CONCLUSIONS
This paper has discussed the need to improve design performance, innovation and productivity and has highlighted the important role of new design tools, methods, technologies and processes in achieving this. However, it is argued that the sheer abundance of tools, methods, technologies and processes available bring about a new set of problems concerning *information overload*, *technology overload* and *analysis paralysis.* Together, these pose a significant barrier to realising a step change in design performance and innovation, especially in the context of today's highly distributed knowledge driven environments. In order to address these fundamental issues, the concept of an Intelligent Design Environment is proposed. This intelligent environment builds upon work in the area of design observation and seeks to extend the paradigm of design observatories from purely passive observation to active intervention. More precisely, the Intelligent Design Environment is one in which in which the tools, methods, technologies and processes are *active* components that respond to the current design episode and where appropriate *intervene*. For the purpose of defining the concept of intervention, a five phase process model is proposed and the potentially vast space of possible interventions within the context of design is highlighted. It is furthered acknowledged that the creation of an intelligent

design environment is a non-trivial activity that requires considerable research effort and technological advances. However, in order to begin to explore the concept, a network of research groups already involved in design observation have theorised about the possible contributions an intelligent design environment capable of design interventions could make. An overview of these possible interventions is presented with respect to the dimensions of problem-solving, decision-making, collaboration and information transformation. These interventions are used as the basis for a vision demonstrator which is illustrated through a hypothetical design episode. This overview of possible interventions and the scenario are used for eliciting the key research and technical challenges inherent for the creation of an Intelligent Design Environment. These are noted to be in the areas of:

1. Complexity of multi-modal monitoring of many actors simultaneously.
2. Practical, legal and cost barriers to storage of massive volumes of information.
3. The difficulty inherent in capture of context and semantic analysis.
4. The challenges in delivering interventions in a manner that is not disruptive to the design episode.
5. Deciding when to intervene, and ensuring the intervention delivers measurable benefits.

The iCORE network is actively involved in addressing these challenges and we invite any other parties with an interest in our activities to contact the corresponding author for further information.

REFERENCES

[1] Pahl G & Beitz W. Tran. by Ken Wallace. *Engineering Design: A Systematic Approach*, 2nd ed., 1996, Springer-Verlag, London.

[2] Ulrich KT and Eppinger SD. *Product Design and Development*. International ed., 1995. Singapore. McGraw-Hill.

[3] Bracewell RH & Wallace KM. A Tool for Capturing Design Rationale. *14th Int. Conf. on Engineering Design (ICED'03).* 19-21st August 2003, Stockholm, Sweden.

[4] Štorga M, Andreasen MM & Marjanović D. The Design Ontology: Foundation for the Design Knowledge Exchange and Management. *Journal of Engineering Design, online edition*. September 2008, Taylor & Francis UK [in press].

[5] Dong A, Hill AW & Agogino AM. A document analysis method for characterising design team performance, *Journal of Mechanical Design, Transactions of ASME*, Vol. 126, No. 3, 2004. pp. 378-385.

[6] Boujut JF & Blanco E. Intermediary Objects as a Means to Foster Co-operation in Engineering Design. *Computer supported Collaborative Work.* Vol 12 No. 2, 2003. pp 205-219.

[7] Törlind P. A Framework for Data Collection of Collaborative Design Research. *Proc. of the Int. Conf. on Engineering Design (ICED'07),* 28-31 August 2007. Paris, France.

[8] Cantamessa M, Duffy A, Hein L & Rimmer D. Design Co-ordination in New Product Development. *Proc. of the 11th Int. Conf. on Engineering Design (ICED'99)*, August 1999, Munich, Germany.

[9] Norese MF, Montagna F & Riva SA. Multicriteria Approach to Support the Design of Complex Systems. *Foundations of Computing and Decision Sciences*, Vol. 33, 2008, pp. 53-70.

[10] Montagna F & Vittone R. Decision Aiding Tools in Product Development: A case study. *Design 2008 Conference*, 19-22nd May, 2008. Dubrovnik, Croatia.

[11] Ericson Å & Larsson T. A Service Perspective on Product Development – Towards Functional Products. *Proc. of at the 12th Int. Product Development Management Conference*. 12-14th June 2005. Copenhagen, Denmark.

[12] Dey AK & Mankoff JM. Designing mediation for context-aware applications, *ACM Transactions on Computer-Human Interaction (TOCHI),* Vol. 12, No. 1, 2005. pp. 53-80.

[13] Reich Y, Subrahmanian E, Cunningham D, Dutoit A, Konda S, Patrick R, Westerberg A & the n-dim group. Building agility for developing agile design information systems. *Research in Engineering Design*, vol. 11, no. 2, 1999. pp. 67-83.

[14] Jones S & Thomas P. Empirical assessment of individuals' 'personal information management systems'. *Behavior and information technology*. Vol. 16, No. 3, 1997. pp. 158-160.

[15] Edmunds A & Morris A. The problem of information overload in business organisations: a review of literature, *International Journal of Information Management*. 2000, Vol. 20, pp. 17-28.

[16] Smith KA. *Teamwork and Project Management*. Basic Engineering Series and Tools. 2002. Second Edition, McGraw-Hill Professional.

[17] Hicks BJ, Culley SJ, McAlpine HC & McMahon C. The fundamentals of an Intelligent Design Laboratory for researching the impact of tools, teams and technologies on information use and design performance. *Proc. of the Int. Conf of Engineering Design (ICED '07)*. August 28-31st 2007, Paris, France.

[18] Törlind P & Larsson A. Re-experiencing engineering meetings : knowledge reuse challenges from virtual meetings, *Proceedings of Challenges in collaborative engineering.* 2006. Prague, Czech Republic.

[19] Milne A & Winograd T. The iLoft Project: A Technologically Advanced Collaborative Design Workspace as Research Instrument, *Proc. of the 14th Int. Conf. on Engineering Design (ICED'03).*2003. Stockholm, Sweden.

[20] Hicks BJ, McAlpine HC, Torlind P, Storga M & Dong A. The issues and benefits of an intelligent design observatory", *Int. Design Conf. – Design 2008*, Dubrovnik, Croatia, May 19-22, 2008, ISBN 978-953-6313-89-1.

[21] Dubberly P. Design and development processes. On the WWW, 2008. Available at: http://www.dubberly.com/wp-content/uploads/2008/06/ddo_designprocess.pdf

[22] Shahrul-Yazid Yahaya, Nooh Abu-Bakar. New product development management issues and decision-making approaches. *Management Decision,* Vol. 45, No. 7, 2007, pp. 1123-1142.

[23] Eckert C & Clarkson PJ. Information Flow in Engineering Companies – Problems and their Causes. *Int. Conf. on Engineering Design (ICED 2001),* 2001, Glasgow, UK.

[24] Henderson K. *On line and on paper*. 1999. Cambridge MA, MIT Press.
[25] Goldberg D. The design of innovation: Lessons from and for Competent Genetic Algorithms, *Lateral Thinking,* Edward De Bono, 1970. 2003, Penguin Books. ISBN 0-14-021978-1
[26] Howard T, Culley SJ & Dekoninck E. Creativity in the Engineering Design Process. *Proc. of the Int. Conf. of Engineering Design (ICED 07)*. August 28-31st, 2007. Paris, France.
[27] Rosenhead J. *Rational analysis for a problematic world: problem structuring methods for complexity, uncertainty and conflict*, 1989. Wiley, Chichester.
[28] Belton V & Steward TJ. *Multiple Criteria Decision Analysis, an Integration Approach.* 2002. Kluwer Academic Publishers, Norwell, MA.
[29] Van der Heijden K, *Scenarios: The art of Strategic Conversation*. 1996. Wiley, New York.
[30] Ostanello A & Tsoukiàs A. An explicative model of 'public' inter-organizational interactions. *European J. of Operational Research*, Vol.70, No.1, 1993, pp. 67-82.
[31] Norese MF & Ostanello A, *Identification and development of alternatives: introduction to the recognition of process typologies, in Improving Decision Making in Organizations* (Lockett A.G., Islei G., eds.), 1989, Springer-Verlag, Heidelberg, pp.112-123.
[32] Montagna F & Norese MF, A Hybrid Approach to Model Design and Development Processes and Evaluate Innovation Opportunities. *Int. J. of Manufacturing Technology and Management*, Vol. 14, No. 3-4, 2008, pp. 379-396. [in press].
[33] Olson GM & Olson JS. Distance Matters. *Human-Computer Interaction*, Vol. 15, No.2/3, 2000, pp.139-178.
[34] Sclater N, Grierson H, Ion WJ & MacGregor SP. Online collaborative design projects: overcoming barriers to communication. *Int. J. Engineering Education*, vol. 17, no. 2, 2001.
[35] Törlind P & Larsson A. Int. CIRP Design Seminar, 16-18 May, 2002, Hong Kong.
[36] AMI Multi-modal meeting minutes. On the WWW, 2009. Available at: http://www.amiproject.org
[37] McAlpine H, Hicks BJ, G Huet & Culley SJ. An investigation into the use and content of the engineer's logbook. *Design Studies*, Vol 27, No. 4, July 2006, Pages 481-504.
[38] Jaimes A, Omura K, Nagamine T & Hirata K. Memory Cues for Meeting Video Retrieval. *CARPE'04,* October 15th 2004, New York, NY, USA, p.74
[39] Prudhomme G & Pourroy F. An empirical study of engineering knowledge dynamics in a design situation. *J. of Design Research*. Vol 6 No.3, 2007. pp. 333-358.
[40] Arıkoğlu ES & Blanco E. Keeping Traces of Design Meetings through Intermediary Objects. *Design theory and research methodology (DTRS7) Workshop*, 2007, London, UK.
[41] Court AW. Modeling and Classification of Information for Engineering Design", Ph.D. Thesis, 1995, University of Bath, UK.
[42] Pitney Bowes Inc. *Workplace Communications in the 21st Century,* White Paper, 2001.
[43] McMahon CA, Pitt DJ, Yang Y & Sims Williams JH. An Information Management System for Informal Design Data. *Engineering with Computers* vol. 11, 1995. pp. 123-135.
[44] Wasiak JO, Hicks BJ, Newnes LB & Dong A. Characterising the Information Content of an Email Corpus from a Software Design Project. *Digital Enterprise Technology, 5th Int. CIRP-Sponsored Conference (DET2008)*, October 22nd-24th, 2008. Nantes, France.
[45] Baudin C, Underwood JG, Baya V & Mabogunje A. DEDAL: Using Domain Concepts to Index Engineering Design Information. *Workshop Notes from the Ninth National Conference on Artificial Intelligence, Intelligent Multimedia Interfaces*, 1991, Anaheim, California.
[46] Štorga M. Traceability in product development. *Proc. of the 8th Int. Design Conf (Design '04)*, 2004, Glasgow, UK. pp. 911-918.
[47] Darlington M, Culley SJ, Zhao Y, Austin SA & Tang L. Defining a Framework for the Evaluation of Information. *Int. J. of Information Quality*, 2008 [in press].
[48] Štorga M, Darlington M, Culley S & Marjanović D. Traceability of the development of 'information objects' in the engineering design process. *Int. Conf. on Research into Design, ICoRD'09,2009*, Bangalore, India.
[49] Huet G, McMahon C, Sellini F, Culley S & Fortin C. Knowledge loss in Design Reviews. *Int. Conf. on Integrated Design and Manufacturing in Mechanical Engineering (IDMME),* 17-19th May 2006, Grenoble, France.
[50] Culley SJ, Davies S, Hicks BJ & McMahon CA. An assessment of quality measures for engineering information sources. *Proc. of the int. conf. on Engineering Design (ICED '05)*. 2005. Melbourne, Australia.
[51] Campbell D, Culley S & McMahon CA. Observations on data relating to user browsing behaviour and usage of electronic information. *6th Int. Conf. on Integrated Design and Manufacturing for Mechanical Engineering (IDMME '06),* 17th-19th May 2006, Grenoble, France.
[52] Weiser M & Seely Brown J. The coming age of calm technology. On the WWW, 1996. Available at: http://www.ubiq.com/hypertext/weiser/acmfuture2endnote.htm.

Contact:

Ben Hicks
Department of Mechanical Engineering,
University of Bath, Bath, BA2 7AY,
United Kingdom
Tel: +44 (0)1225 386881
E-mail: b.j.hicks@bath.ac.uk
Web: http://www.bath.ac.uk/idmrc