INTERNATIONAL DESIGN CONFERENCE - DESIGN 2014
Dubrovnik - Croatia, May 19 - 22, 2014.

A FRAMEWORK FOR THE DEVELOPMENT OF CHARACTERISTIC SIGNATURES OF ENGINEERING PROJECTS

C. M. Snider, S. L. Jones, J. G. Gopsill, L. Shi and B. J. Hicks

Keywords: signatures, knowledge, digital objects

1. Introduction

The activity and practice of globally distributed design and manufacture has now emerged as a fundamental characteristic of modern engineering. As such engineering work is highly distributed, multi-national and heavily dependent upon digital objects that define the engineered product, the process by which it is designed and the process by which it will be manufactured.

One of the key drivers for this shift – hitherto based on cost alone – is now increasingly the geographic availability of expertise and skilled personnel. For example, in a recent address Tom Enders, Airbus's CEO, highlighted the relative intellectual disarmament of the UK/EU and the increasing importance of development teams in India and China [Enders 2011]. It is not only the increasing globalisation of design and manufacture that complicates the delivery of engineering products. So too does the complexity that in a variety of forms is increasingly present in today's artefacts and systems, ranging from large, long-life, multi-domain engineering systems to consumer products and software.

This highly distributed nature of modern engineering combined with the complexity of today's engineering artefacts mean that a multitude of digital objects are now employed. The communication tools include email, instant messaging, video conferencing and social networking and the digital objects (DO) include, for example, spread sheets, CAD models and specialist simulation models. It follows logically that the outputs of these tools (the DOs) are related in a number of fundamental ways that are not currently understood, but could provide insights which can aid engineering management.

By way of examples, a small machine or software project (<£1M) can involve 20+ contributors (engineers from various disciplines, customers, subcontractors, administrators, etc.) generate 20,000+ emails, 3,000+ reports and presentations, hold 500 meetings, generate 1,000+ models (versions) and 40 prototypes [Regli 2010]. In contrast, design, construction and commissioning of a building can span 5 years, involve 100s of project members, 100,000+ emails, 15,000 reports and presentations, 2,000+ meetings and 5,000+ models/representations [Watson 2012].

The premise of the work presented in this paper, and in the wider research project, is that associated with each of these digital objects is inherent meaning that is not currently accessed and utilised to its full extent. For example, given that many digital objects relate to a certain subject, their creation and modification dates indicate times at which work on that subject was occurring. Although basic, this provides one example of how an understanding of the evolution of digital objects during a project might provide insights and value. To begin to explore this potential this paper presents a framework by which digital objects can be studied in detail, and used to provide useful information through comparison with what are referred to as "signatures" of digital objects; which are in turn identified through historical cases and direct study. The paper summarises the results of a review of the information used by engineering project actors; and two examples of potential valuable information that are automatically produced by analysis of the evolution of DOs are presented.

1.1 Modern Engineering

As previously stated modern engineering is critically dependent upon electronic communication and digital objects, which have exploded in terms of their: prevalence of use, volume of content, variety of type and overall numbers. While this explosion has been necessary and beneficial at the detailed application level, it has resulted in overload of information and communication, and fragmentation across individual and organizational digital objects and records with different access and ownership rights. Additionally, the communication and information evolve very rapidly and often across organizations and teams meaning that no individual or management group is continuously up-to-date.

The consequences, in the context of complex engineering projects, are that: *potential issues can be almost impossible to identify early and mitigate; progress monitoring, control and performance measurement are all but impossible; and opportunities to innovate and maximize value are seldom pursued.* Thus, effective management and control of collaborative engineering projects and engineering work is highly challenging and problematic.

The challenges of collaborative engineering concern all sectors from civil, aerospace, automotive and pharmaceuticals, to the creative industries. As example, one high-profile cost overrun experienced within the aerospace sector is that of the the Boeing 3 Dreamliner (over two years late and $10 billion overrun [Drew 2009]). The importance and impact of the challenges of distributed design and manufacture of complex products is set out in a recent report by the US National Science Foundation which reported that the total value of delay and cost overruns stands at $150 million each day for the US Department of Defense alone [NSF 2010]. While such figures are unavailable for the UK it is likely that a similar relative magnitude of cost is incurred by UK industry.

It follows that dimensions of management and control include but are not limited to: team cohesion; effectiveness of collaboration and co-creation of digital objects; the control of intellectual property; decision making and rationale capture; uncertainty and problem solving; interface negotiation and concessions; contractual agreements; risk; costing; and process monitoring. In addition there are also implications for completeness, access and reuse of design records and learning from previous projects.

It is these issues that the framework presented in this paper begins to remedy. Its role within the wider project is to provide the means of association between digital objects and information useful to each identified dimension.

2. A Framework for Study

It follows from this discussion that there is an opportunity within research to study the relationship between the highly complex world of modern engineering, and the vast array of outputs (digital object and communication) that are produced as part of the modern engineering process [Hicks 2013]. From this study and the understanding gained, there is then opportunity for the formation of a multitude of knowledge tools – collecting, categorising, and studying digital objects and communications, with the goal of identifying useful patterns embedded with meaning.

In order to create the process by which useful tools can be developed, it is first necessary to develop a more detailed understanding of digital objects in the real world, the patterns that they may imply, and the potential meaning that these patterns hold. To this end, a research framework has been produced.

This framework forms a clear and direct relationship between digital objects themselves – the multitude of files that are produced as part of the typical engineering process - and the activities completed by actors within the engineering process, to whom any tools produced must be of use. It also then highlights the role of analysis upon digital objects, the nature of information that analysis must produce, and the feedback of such information into the activity of project actors. It is the purpose of the framework to form such a consistent connection – demonstrating the manner in which meaning can be generated from DOs, that can by study be connected with information that is of use to an engineering actor. It is the purpose of this section of the paper to present this framework, following which Section 4 will provide examples of its application.

2.1 The Research Framework

The purpose of the framework here described is as a description of the understanding that can be gained from the study of DOs, rather than as a framework of projects, their management, or the specific structures extant within engineering. As a result, it must remain broad in its description, to maintain compatibility with the wide breadth of project management structures and engineering activities that are utilised throughout the engineering field. The framework takes the form of a feedback loop, as commonly seen in control theory, and is as illustrated in Figure 1. This framework highlights four distinct areas for research that must be studied in order to produce useful information from the digital objects produced within engineering activity, each of which shall be described in detail within this section.

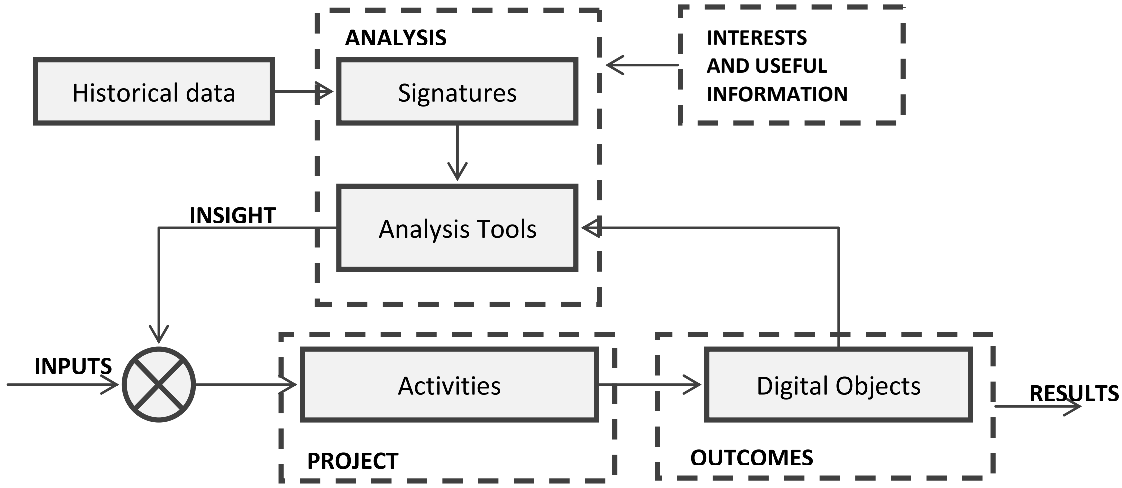

Figure 1. The research framework

2.2 The Engineering Project and Activites

The first area within the framework is the project itself, and the activities completed by actors within it. Based on the fact that DOs are produced as a result of discrete engineering activity, their analysis provides the means to learn about the activity completed by project actors, and by extension the project they were completed within. For example, a slowing in rate of production of DOs in a project could evidence a lack of actual activity of project actors, which could in turn stem from a lack of understanding or lack of resource. Both of these causes are features of the wider project and community of its completion.

The project and activity within it is classified in this framework according to the method used in Activity Theory [Kaptelinin et al. 1995], which states that an activity can only be completely understood with consideration of the situation in which it is completed. This situation describes the elements of the project that may influence the activity of project actors, and hence the DOs that they produce. Following activity theory, the six elements that describe the project are then [Bellamy 1996]:

Subject: The person or people completing the activity.

Rules: The process, policies and standard which the subject follows within the activity.

Community: The social structure to which the subject belongs.

Division of Labour: The hierarchical structure and roles within which the activity takes place.

Tools: The tools that are available for use in the activity.

Object: The purpose or output of the activity.

By study of DOs, this research proposes the possibility of providing information about each of these elements within the specific project, and under the influence of which activity takes place. Understanding of these elements then provides understanding of the wider project and provides the opportunity for useful information to be generated. For example, through analysis of email communication, it is possible to learn about the community within the wider project and related activity, leading to potentially useful information such as the occurrence of communication breakdown.

This section of the framework therefore provides structure to the subject of analysis, highlighting and contextualising the results of analysis of DOs and the information that is produced as output.

2.3 Project Outcomes and Digital Objects

Any DO has been described within this work as an output (in whole or part) of activity. When considered in context of the wider engineering activity and the purpose of the project under completion, this then means that a DO can be the output of activity itself (such as a CAD drawing of a specific part to send for manufacture), or part of the process of development of the output of activity (such as the part file from which the drawing is made). Both of these DOs are subjects for analysis.

More formally, DOs are defined in this work to be *any digital file or collection of files for which a distinct boundary can be described.* By this definition, the framework is able to remain flexible depending on the level of granularity at which they are expected to be of use. For example, should analysis of individual CAD part files prove most useful, then the each individual file will be classed as a digital object. Should a CAD file database prove most useful, then the database itself (thereby containing many individual files) will form the digital object.

In order to understand DOs and the method by which they can be analysed, this work classifies according to their intended function, and their properties (termed *attributes*). There are considered to be four primary categories of digital object based on intended function:

Communication: Any object used to transfer information between multiple actors (e.g. email)

Representation: Any object used to display properties of a design output, at any stage of development (e.g. CAD file or sketch).

Record: Any object used to form a formal record, to be stored for future use (e.g. report, database).

Analysis: Any object used for the purpose of generation of information (e.g. FEA analysis, graphs).

These categories are non-mutually exclusive and have potential to change for each digital object throughout its life-span. For example, a *representation* object (such as a CAD part file) may initially be used as part of the design development process; following which it is sent in a communication to another engineer to act as a piece of information for the purpose of interfacing (and hence as a *communication* object). Through categorisation by function with possibility to consider both initial intent and actual use throughout the objects life, there is broader potential for identification of meaningful patterns from data. For example, analysis of all *representation* objects may generate useful information (such as rate of progression of the design process); as may the use of a *representation* object as a *communication* object indicate useful information (such as a problem with a particular part or assembly).

Separate to their function, the framework describes digital objects through what are termed *attributes*. Each *attribute* describes a property of a digital object, and has a value associated with it. Attributes are placed into four discrete categories.

The four attribute categories are defined as follows:

- *Physical:* The properties of the digital object that describe it as a physical artefact. E.g. Size, creation data, storage location.
- *Content:* The properties of the digital object that describe what it contains. E.g. (For a CAD part file) number of faces, total volume, number of features.
- *Context:* The properties of the digital object that describe its wider context within the scope of the wider company and process. E.g. Accessing department, process stage at which created.
- *Semantic:* The properties of the digital object that describe its importance within the process. E.g. importance, provenance, level of finality.

The purpose of defining these four categories of digital object is to form a widely inclusive and complete method of description, without the need for highly specific and constantly evolving categories. For example, to form a list of all attributes that can be considered as describing the content of a CAD file is a highly difficult task, which would require much refinement and evolution. Conversely, forming a higher level category allows consideration and analysis of content attributes, while accepting that the list of types of content attribute will grow and evolve with time.

Through studying the attributes of a digital object through each of the categories, it is possible to develop a detailed description of it, and its place within the wider company and engineering process. For example, the *content attributes* of an object determine what it is (and by extension what it may be used for), such as an email (contains text, sentiment, information, etc). *Physical attributes* determine the properties of the email as an object (e.g. sent to/from, total length, number of involved people).

Semantic attributes determine the place of the email within the process (e.g. sent by high-ranking employee, contains expert information). *Context attributes* describe the wider context of the email (e.g. relating to project brief, sent by manufacture team, sent to supplier).

It is from the digital objects and their attributes that all analysis occurs, and hence it is the digital objects and their attributes that form the base level of the framework. It is from these, then, that useful information for engineering actors is derived.

2.4 Interests and Useful Information

Essential to completing useful analysis is the need to understand and generate information that is useful to project actors. This is a broad question, with varying information likely of importance dependent on hierarchical postion within the company, role of the actor, focus of current activities, time or place within the engineering process, etc. Within the scope of engineering projects there are also many actors to whom tools could be targeted, including project management staff, administration, legal teams, sales and marketing, as well as the design engineers, manufacturing engineers, maintenance engineers, etc. who are involved throughout the process. To each of these classes of actors there is a likely variation in information that is useful, including that which may relate to each dimension listed in Section 1 (i.e. risk, IP diffusion, progression monitoring). There is therefore a need to identify information of primary use and value within the typical engineering project, in order to develop broadly applicable tools.

One source of understanding of useful information is in understanding of the actual activities of project actors and their information needs within, as derived from a combination of literature and study. Activities of engineers, for example, have been studied in detail from both a process model perspective [Pahl and Beitz 1984], [Pugh 1990] and from the perspective of behaviour research [Gero 1990], [Cross 2004]. Similarly, project management literature describes many taxonomies of management activity, such as the PMBOK guide [PMI 2008], or the classical PRINCESS management functions [Mahoney et al. 1965]. However, as has been highlighted in project management literature [Carroll and Gillen 1987], there is some confusion as to the completeness of such taxonomies, their applicability to real life, and their ability to accommodate the complexity of the activities completed by actors on a regular basis. As a result, while it is possible to use existing models of activity to contextualise and form a basic understanding of tools that may be useful, due the possibility of inaccuracy or lack of appropriateness of some models and the possibility that engineering actors will not complete the activities described, they form an incomplete basis on which to build tools. In order to counter this uncertainty, it is necessary to directly study the activities completed by engineering actors, and their actual information inputs. In terms of engineers, some research of day-to-day activity has been completed, both in assigning observed activity to that of engineering process models [Hales 1986]; and in more specific terms, categorising actual actions of engineers separate to the process model activity in which they were working [Robinson 2010]. In addition, other researchers have studied the information that engineers desire and associated use [Marsh 1997], [Heisig et al. 2010]. This work has highlighted the importance of providing engineers with information regarding past work such as rationale, changes made and difficulties in design; as well as more general information such as status of progress of others, and suggestion of appropriate tools or methods to employ in a given situation.

A second alternative to identifying useful information is through understanding of the activity that leads to project failure, such as is researched within the field of project management (see [Pinto and Mantel 1990], [Collins and Baccarini 2004]). By this method, information may be provided that warns of the occurrence of specific project failure factors. For example, information that highlights potential barriers in communication (through study of the project *community*), a lack of expertise (through study of DOs produced by project *subjects*), or a lack of broad understanding and clarity of the purpose of the project (through study of DOs that describe the project o*bjective*).

In both of these methods, it is the identification of information that is useful to project actors that is important. Although such research is ongoing, its purpose can be contextualised within the framework. Through the analysis of digital objects, themselves contextualised as an output to activity completed within a specific project situation, useful information can be generated. This information acts either to provide input to actors' activities, according to their information needs, or will warn of potential issues within the wider project. In both cases, the information provded will act as a discrete input into the activity of a project actor, either those producing the digital objects or another, and will be used to improve the result of the project or its management.

2.5 Analysis of digital objects

Given a digital object (or group of) and its attributes, some analysis must occur in order to provide the engineering actor with useful information. In this statement then, there is the assumption that contained within the collection of attributes of any digital object (or object group) is inherent meaning, and that through some form of analysis it can be derived. To describe the relationships between this inherent meaning and the digital objects themselves, the framework defines three elements; *profiles, patterns, and signatures*.

Both profiles and patterns share many similarities, each being represented by digital objects (and their attribtutes) as identified in the engineering project under analysis. It is these that form the unit of analysis that produces useful meaning to the actor, specific to their project.

A profile is a set of values for attributes of a digital object at a single point in time. For example, the length of a single communication, the sentiment within (e.g. positive or negative), and the number of people communicated to. A pattern relays the change in a set of values for attributes of a digital object with time. For example, how the length of communications changes, how sentiment changes, and the variation in the number of people involved. Both profiles and patterns therefore produce a description of a digital object, either at a single point in time or across multiple points.

In order to assign meaning to profiles and patterns, they must be compared to signatures. A signature here is a known profile or pattern, with a known implication or meaning. It is therefore through comparison of profiles and patterns existing in a project against known signatures (of the same attributes) that useful information can be generated for the concerned actor.

There are a number of notes to be made about signatures and the comparison to form information. First, signatures must be identified through historical cases or direct study. Any signature consists of a set of attributes from one or more digital objects with known values, and an associated and validated meaning or implication within the engineering process. Signatures must therefore be created through analysis of known sets of attributes with occurrences within the wider engineering process. Second, there are signatures for both profiles and patterns. Both are thought to be capable of holding inherent information; although the meaning and applicability of signatures or profiles and patterns may vary with digital object and desired information. Third, a signature is always *of something*. It is the purpose of the signature to allow analysis which provides information. Each signature is therefore defined by the information that it provides.

For example, through study, it may be found that a certain increase in the value of an attribute occurs before the appearance of a major problem in an engineering project. In this case, following appropriate validation, this increase in a certain attribute is identified as a signature of the occurrence of the specific type of major problem. Therefore by monitoring the specific attribute within each engineering project and comparing its state (or pattern) against that described by the signature, a warning of the impending occurrence of the major problem can be formed. As a more tangible example, should it be found that a decrease in communication quantity and increase in negative sentiment consistently preceed communication breakdown between teams; the monitoring of communication quantity and sentiment could be used as a warning tool.

2.6 Summary of the framework

The framework here proposed forms a structure by which useful information can be derived from a digital object (or group of digital objects), based on known historical or observed cases.

Any digital object is the output of activity, which was performed as part of a wider project. As a result, analysis of digital objects and patterns in their creation, modification, or attributes, will provide information regarding the project itself.

The attributes of any digital object can be classed as a profile of that object at a single point in time, or can be traced to form a pattern of change of that object over time. It is these profiles and patterns that form the unit of analysis of the framework. Once identified, all profiles and patterns of attributes of a digital object can be compared with *signatures*; profiles and patterns of *the same attributes* that have a known meaning. These signatures are identified through study or historical cases. Through comparison between the signature and the profile or pattern, useful knowledge and insight can be generated; such as an indication of the likely occurrence of a specific event, comparison between a current state and historical cases, or prediction of the likely manner of project progression.

Through these elements and this process, the framework is able to form a connection between the specifics of the multitude of digital objects produced during modern engineering projects, and information that is useful to those working within or around the engineering project. Specific examples of potential useful information from real data are given in Section 4.

3. The Framework in Use

To illustrate the use of the framework and the potential knowledge and insight that it can produce, two preliminary analyses of real datasets have been performed. While currently unvalidated, these datasets each provide tangible examples of useful signatures that can be formed automatically from the analysis of digital objects. Each potential signature given is of *progression* within specific activities or the engineering process as a whole; as a response to the work of Marsh [1997], who demonstrated that the higher proportion of information requests of an engineer were for some status with time.

3.1 Example 1 – Pattern in attributes of CAD files

The first example concerns the creation and changes of CAD files within a single system, measured over time. Each file is determined as a digital object, with the attributes of measurement of: date of creation (*physical attribute*), date / dates of modification (*physical attribute*), and associated sub-system (*content attribute*).

Source of Data

The data was collected by the monitoring of the files of a University Formula Student team – an involved project completed globally by manu universities, with the purpose of designing a fully-functional racing car. During the design and development phases of the project, all participants used a single shared file space, which was periodically copied in its entirety to a storage drive. This created a full copy of each file produced by the project team, with full version history and associated files. The project itself occurred over 12 weeks and involved 30 trainee engineers. In total, they created 1637 CAD files and made 8508 modifications; leading to 10145 data points.

Attribute Pattern and Potential Signature

Figure 2 shows two matrices; one of the creation of CAD files categorised by sub-assembly to which they belonged, and one of the modification of CAD files by the same categorisation. In each, the appearance of a darker shade indicates a higher occurrence. These matrices form a pattern of attributes of the group of digital objects – the creation and modification dates of CAD files with time, and can be produced automatically through monitoring of actual files produced.

Although no further validation has been completed at this point, this pattern could demonstrate useful meaning for the purpose of process monitoring (thereby as a *signature of progression*). For several sub-systems, particularly those highlighted, there is a consistent pattern of creation of files, followed by a significant period of modification, followed by a second significant period of creation. This is thought to be characteristic of the process by which the design is formed. Initially, the designers create a series of early representations of each sub-system according to ideas that have been proposed. As the design progresses, changes are made to these files according to the increased understanding of the designers and as required by other changes within the systems. Once an equilibrium has been reached and the modelled design has reached a suitable specification, final versions of each file are created, to be used in manufacture and beyond.

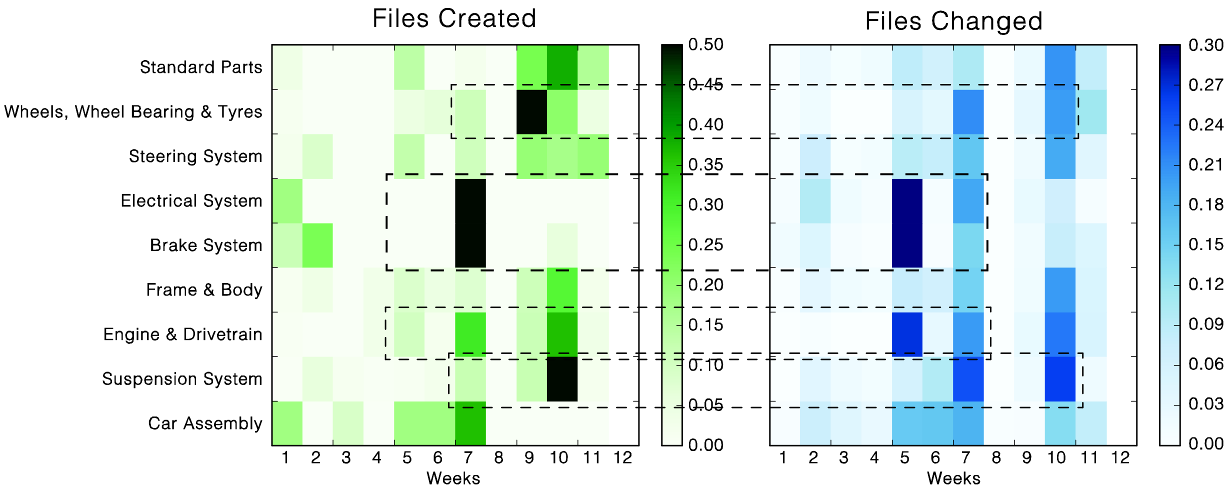

Figure 2. Creation dates and modification dates of CAD files

This pattern then suggests a potential signature of use. By monitoring the production of CAD files, their modification, and associated sub-system, a tool may be able to automatically indicate stage of the design process (also potentially linking to time remaining until completion). For example, when in a period of significant modification to a group of files from a single sub-system, it could be stated that the sub-system is in a phase of design iteration. When the modification rate descreases and the creation rate increases, it could be stated that the sub-system is in a phase of finalisation. This information therefore provides status of the design process which may prove useful to several involved parties; for example, informing designers of the progress of their colleagues (thus allowing time to be allocated to different activities more appropriately), or informing managers of the state of design, thus giving some indication of rate of progression and lilekly completion dates.

3.2 Example 2 – Pattern in email types

The second example concerns emails sent between employees at a multi-national engineering consultancy. Each individual email is considered to be a digital object (excluding threaded or repeated text stemming from replies or forwards), with measured attributes of number of recipients (*physical attribute*), length of body text (*physical attribute*), number of attachments (*physical attribute*), and number of cc'ed recipients (*physical attribute*).

Source of data

The dataset consisted of more than 5000 emails from a multi-national engineering consultancy, working on a marine engineering project over a period of three years, and involving 1045 unique addresses. All emails sent as part of the project were automatically copied and stored to a database. This dataset has previously been reported upon in Wasiak et al. [2010] and Hicks [2013].

Attribute Pattern and Potential Signature

Using the Expectation Maximization (EM) Clustering Algorithm in Weka 3.6 (http://www.cs.waikato.ac.nz/ml/weka/downloading.html), the emails were automatically clustered into groups with similar attribute values. These clusters were then mapped according to their occurrence through the project and the stages of the design process (see Figure 3). As example, cluster 0 contained very short messages to a single individual, although copied to a groups, and cluster 5 contained longer (but still short) messages, sent to a group and copied to a large group. Further detail of the analysis method and results of this example are to be published in future work.

Although again in unvalidated form, there are numerous potential features of this dataset that could form a useful signature of progression. For example, short, one-to-one messages are very important through the project (cluster 6) but descrease in proportion in assembly and testing to short group messages (cluster 5). Another pattern is in cluster 1 (emails with many attachments) which do not appear in quantity until sub-system manufacture stages. Therefore scope exists to study correlation of the appearance of different cluster types with design activity and design process stage. Current work is investigating the relationship between the signatures identified by Wasiak et al. [2010] based on content and these clusters.

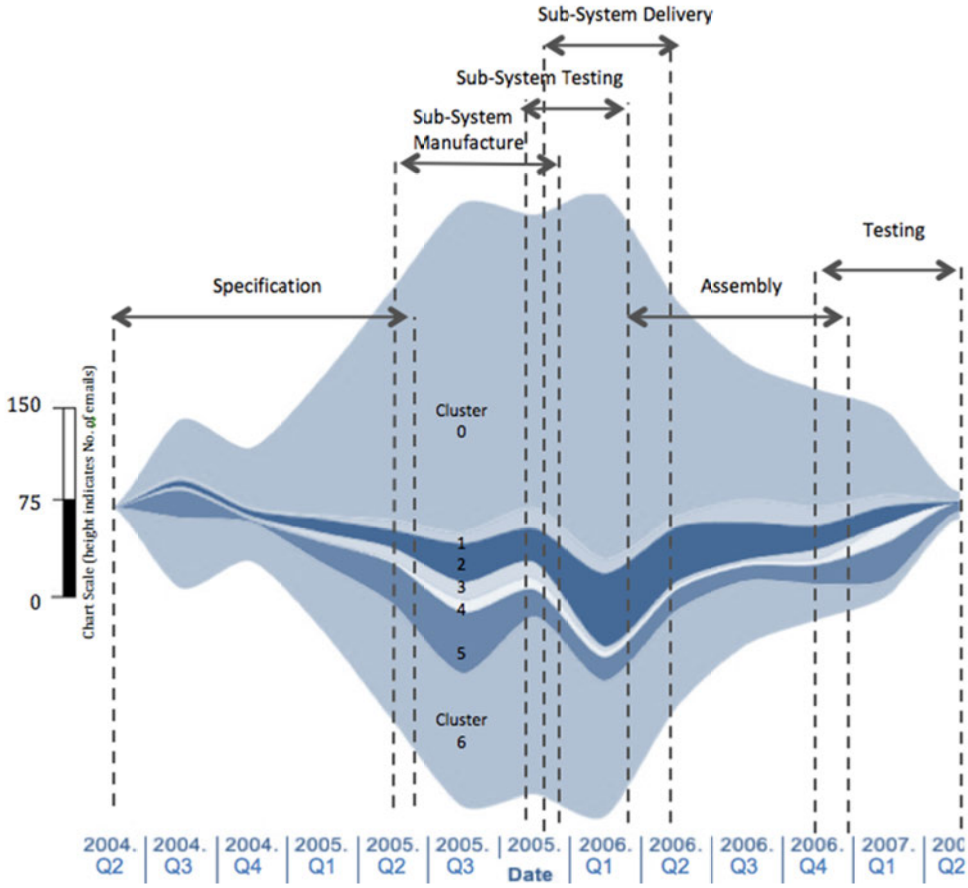

Figure 3. Clusters of emails with time

Should both of these patterns hold true across multiple engineering projects, they may prove a useful and automatic method of indicating the current stage of the design process at which work on the project is occurring, without need for any direct consideration of content of the emails collected.

4. Discussion and Conclusions

Modern engineering projects are often large-scale, high cost investments involving highly distributed teams. As a result, engineering projects and the people working within are highly dependent on electronic communications and digital objects, which are produced in volume. It is the premise of this work that associated with these digital objects is inherent information which, through careful analysis, can be automatically identified and provided to actors working within the wider project. Accordingly, there is scope within engineering projects to produce a large amount of useful information that can be used both to streamline and enhance current working procedures.

To this eventual end, this work has presented a framework designed to allow the association of any digital object with inherent meaning according to consistent and automatically identifiable categories. By describing a digital object according to its attributes and its function it is possible to produce profiles and patterns, collections of attribute values at a single point in time or over a range. These profiles and patterns can then be compared against known "signatures", collections of attribute values with a known meaning or implication in the wider project. Through this comparison, information regarding the state of a current project can be generated, which can in turn be used by the engineering actors. The framework allows detailed description of each digital object in an tangible, quantifiable, and automatically derivable manner. Through the classification of function, each digital object can be tied to its intended purpose and use in the engineering project, and hence to the actors and stages at which it may help elucidate knowledge and insight. Through the attributes of digital objects, the framework describes the varying subjects of inherent information that they may help to provide, and hence provide focus for study aiming to identify signatures – should information of progression be desired, attributes relating to time and project development should be studied. These categories also provide subjects for study of inter-relation of attributes and digital objects – by completing detailed descriptions of DOs that are conducive to automatic analysis, less tangible signatures may be found. Within the two examples given, the framework has highlighted patterns that may prove associated with progression (physical attributes with a time dimension) and those associated with specific areas of the project. As a result, it is possible to create a connection between a measured time dimension and the engineering projects. In example one, the sub-assembly under development (content attribute) is associated with the time of creation (physical attribute), and patterns of progression are implied. Similarly, example two uses content attributes (times of activity) to build a profile of an engineering repair project with time. Each example also implies potential meaning that, through validation, can be associated with useful signatures.

Further work from this paper must be completed in two areas. Firstly to identify primary information of use to varying actors within engineering projects, that is broadly applicable across projects and people. Second to validate suggested patterns within each example, and to identify and validate further patterns according to the desired output information, thereby forming reliable signatures.

Acknowledgement

The work reported in this paper has been undertaken with support from the Engineering and Physical Sciences Research Council (EPSRC) at the University of Bristol.

References

Bellamy, R. K. E., "Designing Educational Technology: Computer-Mediated Change", In: NARDI, B. A. (ed.) Context and Conciousness: Activity Theory and Human-Computer Interaction. Boston, MA: MIT Press, 1996.

Carroll, S. J., Gillen, D. J., "Are the Classical Management Functions Useful in Describing Managerial Work?" The Academy of Management Review, 12, 1987, pp. 38-51.

Collins, A., Baccarini, D., "Project Success - A Survey", Journal of Construction Research, 5, 2004, pp. 211-231.

Cross, N., "Expertise in design: an overview", Design Studies, 25, 2004, pp. 427-441.

Drew, C., "A Dream Interrupted at Boeing", (Online), The New York Times, Available at: <http://www.nytimes.com/2009/09/06/business/06boeing.html?pagewanted=all&_r=0>, Accessed 4th December 2013, 2009.

Enders, T., "Airbus CEO address", at SAE Aerotech Conference. Toulouse, France, 2011.

Gero, J. S., "Design Prototypes: A Knowledge Representation Schema for Design", AI Magazine, 1990.

Hales, C., "Analysis of the Engineering Design Process in an Industrial Context", PhD, University of Cambridge, 1986.

Heisig, P., Caldwell, N. H. M., Grebici, K., Clarkson, J., "Exploring knowledge and information needs in engineering from the past and for the future - results from a survey", Design Studies, 31, 499-532, 2010.

Hicks, B. J., "The Language of Collaborative Engineering Projects", ICED13: International Conference on Engineering Design, Seoul, Korea, 2013.

Kaptelinin, V., Kuutti, K., Bannon, L., "Activity theory: Basic concepts and applications", Human-Computer Interaction, 1015/1995, 1995, pp. 189-201.

Mahoney, T. A., Jerdee, T. H., Carroll, S. J., "The jobs of management", Industrial Relations, 4, 1965, pp. 97-110.

Marsh, J. R., "The capture and utilisation of experience in engineering design", PhD, University of Cambridge, 1997.

NSF, "NSR workshop on engineering systems design", (Onlin)], Available: <http://vddi.org/ESDW-report.pdf>, Accessed 4th December 2013, 2010.

Pahl, G., Beitz, W., "Engineering Design: A Systematic Approach", London, Springer, 1984.

Pinto, J. K., Mantel, S. J., Jr., "The causes of project failure", Engineering Management, IEEE Transactions on, 37, 1990, pp. 269-276.

PMI, "A guide to the project management body of knowledge (PMBOK Guide)", Newton Square, PA, Project Management Institute, 2008.

Pugh, S., "Total Design: integrated methods for successful product engineering", Harlow, Prentice Hall, 1990.

Regli, W., "Digital Engineering Archives", (Online), Philedelphia, PA: Drexel University, Available at: <http://www.digitalpreservation.gov/partners/documents/digarch-regli.pdf>, Accessed 4/12/2013 2013, 2010.

Robinson, M. A., "An empirical analysis of engineers' information behaviours", Journal of the American Society for Information Science and Technology, 61, 2010, pp. 640-658.

Wasiak, J., Hicks, B. J., Newnes, L., Dong, A., Burrow, L., "Understanding engineering email: The development of a taxonomy for identifying and classifying engineering work", Research in Engineering design, 21, 2010, pp. 43-64.

Watson, J., Keynote address at the University of Bath, 2012.

Mr. Chris Snider, Research Associate
University of Bristol
Mechanical Engineering
Queens Building, Bristol BS8 1TR, United Kingdom
Telephone: +44(0)1173315724
Email: Chris.Snider@bristol.ac.uk