Engineering Project Health Management: A computational approach for project management support through analytics of digital engineering activity

Chris Snider, James A. Gopsill, Simon L. Jones, Lia Emanuel, and Ben J. Hicks

Abstract—**Due to the situational and contextual individuality of engineering work, the in-progress monitoring and assessment of those factors that contribute to success and performance in a given scenario poses a distinct and unresolved challenge, with heavy reliance on managerial skill and interpretation. Termed *Engineering Project Health Management (EPHM),* this paper presents a novel approach and framework for monitoring of engineering work through data-driven and computational analytics that in turn support managerial interpretation and generation of higher-level, context-specific understanding. EPHM is formed through the first adaptation of *Integrated Vehicle Health Management* (IVHM) to the field of engineering management; an approach that has been used to-date for machine monitoring and predictive maintenance. The approach is applied to four industrial cases, which demonstrates the generation of project-specific information. The approach thereby acts to increase understanding of engineering activity and work state, and is complementary to existing managerial toolsets and approaches. A key tenet of the adaption of IVHM is to place the manager in a central role, supporting their professional judgment while reducing investigative effort.**

Index Terms— **Engineering Management, Project Management, Project Success Factors, Process Monitoring and Control, Integrated Vehicle Health Management, Project Performance**

Managerial Relevance — **The EPHM approach provides a framework through which detailed description of engineering activity is computationally generated; information that is vital in support of managerial understanding, and previously highly challenging to extract. The approach presents an objective and systematic approach of providing real-time, context-specific information, in support of managerial interpretive and decision-making processes, and that can be used in combination with existing managerial toolsets.**

I. INTRODUCTION

IN concert with globalization and driven by the development age, modern engineering management faces challenges in scale [1], complexity [2], [3], risk [4], [5], and geographic distribution [6], [7]. Correspondingly, their cost and the implication of issues and delay are significant. In cases such as construction and aircraft design there can be many thousands of engineers concurrently working on thousands of components across continents, making management control and monitoring of process and performance highly challenging, even for experienced managers. For these reasons, much recent work has been dedicated towards the measurement and monitoring of performance [8], project success factors (see [9]–[14]), and studies of project failure (see [15]–[18]). By assessment of the make-up of a "good" engineering work scenario, managers judge and attempt to operate towards these ideals in their own.

This goal is however stymied by the fact that engineering operations and projects are replete with variety, where the context of each defines an individual set of goals for completion and conditions of operation [19]. Within the engineering field alone, subjects of work range between design, modelling, planning, production, and maintenance tasks within electronics, automotive, aeronautic, and construction systems; and involve single engineers to the coordinated, international efforts of tens of thousands [20], with many different cultural backgrounds. Directly coupled with variety then also come associated issues of context [10], [19], [21]. The formation, monitoring, and management of "good" projects or operations is thus challenging; when each scenario is individual the structure and process that it follows may be unique, and conditions that lead to success highly variable. As a result, the attainment of an ideal formed from top-down analysis of success requires careful consideration in its applicability.

This leads to the problem statement of this work. As unique and context-dependent entities, the management and success of

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engineering work requires individual and distinct analysis and domain understanding. Whereas literature presents a synthesized generalization of factors for success, it is challenging to determine importance and impact of each for every unique scenario.

To support such management challenges, this work proposes an approach to engineering activity monitoring and managerial decision-making rooted in low-level, data-driven analysis. Adapting the approach of *Integrated Vehicle Health Management* (IVHM) [22]–[25], this paper presents a framework for the automatic and context-specific generation of analyses of engineering activity, and the processes by which such information may be used to affect informed and context-applicable decision-making.

Through utilization of low-level data extracted from the in-operation characteristics of a system and in-built knowledge of system working principles, IVHM generates diagnoses and prognoses of current and future system performance automatically, for action by system engineers. In adaptation to the engineering management scenario this framework promotes the active monitoring of in-progress activity through large-scale and broad-spectrum data analyses, to generate a data-driven and context-specific understanding of work state and, through managerial interpretation, promote understanding of project health.

The remainder of this article is organized as follows. Section II presents a literature review of metrics of assessment of engineering projects and operations, and of the approach of IVHM. Section III presents an adaptation of IVHM to engineering management. Section IV presents four distinct cases of analyses following the IVHM approach. Section V concludes with consideration of approach feasibility and further work.

II. LITERATURE REVIEW

This section first discusses the approaches to performance monitoring and assessment present in extant literature, and their application to context-specific engineering scenarios. Following, it presents and reviews the approach of IVHM, including the literature gaps leading to the approach and framework presented within this article.

A. Monitoring and assessment of performance, success, and state

The monitoring of engineering work progress and judgement of success are complex and context-sensitive tasks.

Initially following the classical "iron-triangle" of project success – time, cost, and quality [26]–[28] – numerous Key Performance Indicators (KPIs) have been proposed to form the benchmark by which a manager can judge the success of ongoing or historical work. By comparison to threshold values, determined individually for each scenario, a manager may judge the state of work and/or output against desired goals. Such KPIs may take many forms dependent on need, ranging from the more traditional and manifest iron triangle, to the more subjective approvals of internal and external stakeholders such as company and end-user [16], [27]. Determination of such

KPIs can hold significant challenge, with potential for variation and an abstract relationship between actual activity and impact on KPIs under scrutiny [27], leading to reliance on estimation. As such, significant managerial challenge exists in measurement of performance or success for a given scenario.

Further challenge exists in determination of those factors that influence work progress, and hence eventual project success, for a given context. Many such critical success factors (CSFs) are identified in literature; [29] present 53 factors for project success in software development ranging from the corporate environment to technology; [30] present 10 over-arching factors associated with failure across general project management, [31] present 88 factors known to influence project performance in engineering projects, and [9] present 12 CSFs based on interview within 70 organizations. Illustrated by this breadth, there is recognition that the influencers of project success across scenarios has significant potential to vary, dependent on work type and context [15], [31]. As such, although the many factors proposed provide a strong base on which to model better practice, there remain difficulties in context-specific applicability.

Such variety impacts activity assessment and monitoring. In management, there is a need for control and understanding of myriad variables, such as scale [1], [32], risk [5], [29], complexity [33], [34], scope [35], and capability [36], [37] and, given high potential for variation between scenarios, it is unsurprising that the reality of individual engineering work manifests in many forms depending on context [19]. The breadth of factors of importance even solely within the engineering domain demands variation in the manner of their management [21], [38], [39], while causes of failure and metrics of performance also vary on a per-field or per-situation basis [3], [10], [40].

With such breadth, complexity, and per-scenario variation both in that which denotes performance (KPIs) and that which may affect success (CSFs), a need exists to aid managers in their detailed understanding of the specific work and activities under their responsibility. Where existing literature provides ample framework by which project success or state may be measured, it also highlights the need for detailed understanding of the specific state on a per-case basis. With myriad factors of influence, many of which may vary in priority, impact, and state, significant managerial effort must focus on the interrogation of each scenario in-progress to support decision-making processes and encourage high performance.

The approach presented within this paper aids such managerial effort through automatic generation of scenario-specific information, namely direct, real-time, data-driven analyses of engineering activity, in support of monitoring and decision-making processes.

B. Integrated Vehicle Health Management

Developed primarily within the aeronautic industry over the last half century [25], [41], [42], and with particular progress in the 2010s [22], [23], [43], IVHM is focused on the inference of high-level understanding of machine performance from low-level operational data. Aiming for autonomy in machine

diagnosis and prognosis, IVHM uses high levels of embedded sensor capability and knowledge of underlying operational principles to predict specific mechanical issues from early warning signs, such as vibration profiles characteristic of high wear coupled with high temperature in a specific component. Through broad spectrum and combinatory data analysis, IVHM aims to allow prediction of the need for maintenance intervention before performance is affected beyond acceptable levels.

In implementation, IVHM frequently employs the Open System Architecture – Condition Based Monitoring (OSA-CBM) framework [44] (see Fig. 1), presenting the vital elements for an effective prognostic system.

Both L1 and L2 are concerned with generation of system-specific data. Due to the variance of machines and associated uniqueness of any given system under analysis, sensor-installation is often bespoke and tailored to the specific operational characteristics of the machine under monitoring. Forming the basis of analysis at higher levels, much effort is dedicated to sensor selection, validation, and pre-processing [24], following which initial analyses will characterize signals and extract features for interpretation.

L3 forms a description of the system under scrutiny, associating sensor readings with known limits devised for the specific case. These are then assessed by the IVHM system within L4 to determine machine health, inferred through comparison between actual state and known fault modes, stating the likely causes of the performance characteristics observed. This is a complex process with no single method capable of encapsulating all applications [23], thus requiring bespoke design on a case-by-case basis.

With sufficient information, L5 takes diagnostic data and calculates likely future trends, such as time-to-failure, based on known characteristic profiles of degradation on the components causing issue. Such data is then analyzed in L6 to provide recommended actions given observed performance

Fig. 1. OSA-CBM Framework, adapted from [44], [79], [80], showing the seven levels required for an effective IVHM system.

characteristics, typically in replacement schedules for components while maintaining suitable operational capability. This data is presented to the engineer in L7 in a streamlined manner, with focus on minimal human interpretation.

C. Engineering Project Health Management (EPHM)

The key purpose of IVHM is in analysis of complex and unique machines, to interpret performance in a manner appropriate to the specific machine, and to detect and predict machine-specific problems. IVHM is thus targeted towards similar issues to those faced in engineering management - individuality of that under study, difficulty in assessment, and a monitoring of a large quantity of variables that may affect activity and performance. The principles of IVHM are thus designed to manage individual systems and machines, providing information that enables engineers to ensure high performance through detailed description of machine activity and, where feasible, diagnoses of issues and prognoses of future state. The principles of IVHM then provide an avenue for such currently extant issues in engineering management to be addressed, the presentation of which forms the purpose of this work.

Through a low-level, algorithmically interpreted evidence base, IVHM encourages direct measurement and monitoring of trends-in-progress, subsequently inferring activity, performance, and issue through comparison to an underlying knowledge base. Accordingly, this work explores the adaptation and application of an IVHM methodology to the discipline of engineering project management, termed Engineering Project Health Monitoring (EPHM). Within, engineering managers are encouraged to use automatic, real-time, low-level, broad-spectrum analyses in support of their scenario-specific understanding, and as basis on which to inform their managerial work and decision-making processes. Adaptation of the IVHM methodology to the context of engineering work provides a novel approach to provision of new levels of work-specific and context-specific managerial understanding.

It is of note that all engineering work is considered of equal opportunity for analysis, in that presence of high quantities of digital files is ubiquitous across modern engineering. As such, while difference may exist in analytics applied, EPHM is applicable in both project and operations contexts.

III. ADAPTATION OF IVHM TO ENGINEERING WORK

IVHM operates through interpretation of sensor output compared to a knowledge base derived from functional, behavioral, and structural understanding of desired machine activity. The principles from which analytics derive and expected sensor outputs are central to interpretation, indicating deviation-from-desired and subsequent diagnoses or prognoses in either steady or temporally dynamic scenarios dependent on machine application and life.

Where IVHM monitors in-operation activity of a machine and recommends maintenance when and where outputs are non-desired, EPHM must monitor the in-progress activity of engineering work, both temporally dynamic and static, support
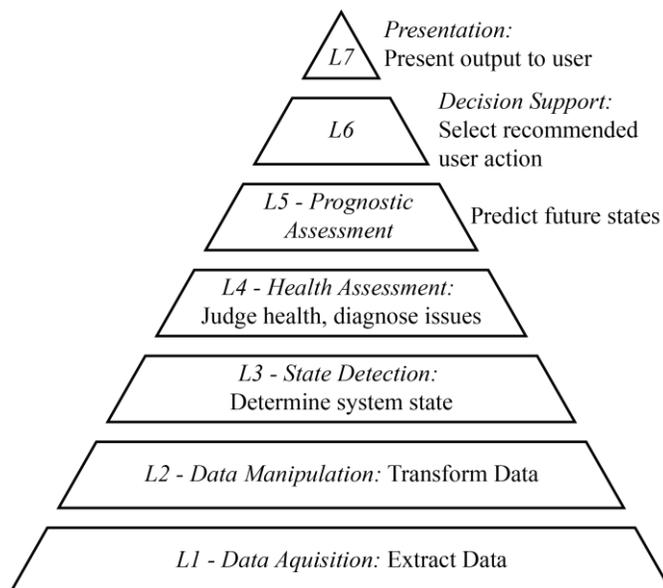
development of detailed understanding, and support action (via decision-making, intervention, etc.) dependent on deviation of such activity from expected or desired states. Through provision of near-real-time analysis of engineering work, EPHM provides a framework and structure through which managerial understanding is significantly increased, while investigative workload is similarly decreased.

To operationalize EPHM with respect to the principles and structure of IVHM several adaptations are needed, namely in unit of measurement (*sensors* as applied to engineering work), interpretation of output, and approach structure. These are detailed in this section, followed by case examples of analysis and application within Section IV.

A. Unit of Measurement

Core to IVHM is the principle of automatic monitoring of actual activity within the machine, with broad analysis selected to capture all aspects of machine behavior. Due to the variety of functions and forms that a machine may take this is a complex and major undertaking [45], with bespoke instrumentation for each case. Dependent on understanding of the activity of the machine and requirements for use, the combinatorial analysis of multiple aspects of machine activity allow higher-level inference of the state of the wider system.

Direct similarity may be drawn in application to the engineering management context, where the activity of personnel is dependent on the multiplicity of internal and external influences and relationships generated by the characteristics of the scenario under which the activity occurs [46]–[48]. Here engineering work is defined as all direct and indirect activities performed by an engineer in execution of their project [49], [50], or as part of their operations. Scenario characteristics and activity performed are therefore inherently inter-linked; although highly complex, dependency between activity and work/scenario state allows analysis of each to imply properties of the other. As in IVHM, this relationship between work/scenario characteristic and activity creates a path between direct analysis and higher-level system health.

As measurement of machine activity in IVHM allows interpretation of higher level system health, this relationship between work/scenario characteristic and engineer activity inherently links low-level activity and higher-level interpretation of project health. As example, properties of engineer communication activity are dependent on such higher-level scenario characteristics as team shared understanding and cohesion [51], motivation and conflict [52], and information structure and availability [53], [54], each of which also hold

TABLE I
CRITICAL SUCCESS FACTORS WITHIN PROJECT MANAGEMENT

Ref.	Critical Success Factor Categories
[29]	*Corporate Environment, Sponsorship/Ownership, Relationship Management, Project Management, Scope, Requirements, Funding, Scheduling, Development Process, Personnel, Staffing, Technology, External Dependencies, Planning*
[30]	*Project Mission, Top Management Support, Project Schedule/Plans, Client Consultation, Personnel, Technical Tasks, Client Acceptance, Monitoring and Feedback, Communication*

relationship to project success [15], [55]–[60]. While less tangible in the engineering management context than the machine of IVHM, the existence of such relationship (although not necessarily in form or priority) remains consistent across engineering scenarios, thus allowing cross-context consistency in analysis approach.

The scale and scope of activity measurement possible will vary in any given case. Following the IVHM approach, engineering activity should be instrumented to as high a degree as feasible. Within modern engineering, which is increasingly enabled by technological development, there is significant scope for monitoring of activity through digital means [61]–[63]; given the reliance on digital tools that is ubiquitous throughout engineering, both in project and operations scenarios, a significant-and-growing amount of digital information is already generated. By capture of all elements of activity feasible within the scenario, using analysis methods applicable across digital industrial engineering systems, a wide evidence base for analysis can be formed.

B. Analysis Factors and User-in-the-Loop

Engineering management is subject to a multitude of CSFs, see examples in Table 1, with varying levels of importance and context-specificity on a per-case basis. IVHM tackles similar breadth, in that the failure modes of complex mechanical systems are many and varied, but greatly differs in the approach applied in their monitoring and management. Using the data generated through its broad analysis of activity, IVHM searches for individual patterns and characteristics that signify traits of performance. By retaining a strong evidence base, rather than monitoring for certain assumed failure modes, IVHM ensures that its analyses are grounded in the context of the machine under study. It therefore encourages pro-active maintenance of the machine, with intervention driven by need rather than higher-level, generalized descriptions of ideal performance. Application of an IVHM approach would therefore provide a similar process within engineering management, aiming to generate detailed descriptions of activity as an evidence base for intervention, and hence allowing management to ground in the specific context rather than generalized ideals.

In IVHM this is an automatic process, enabled by direct association of machine activity with mechanical performance. All mechanical systems are governed by physical principles, creating direct theoretical guidance between operational characteristics and potential underlying cause. For example, the relation between vibration and wear forms an avenue for study in its own right, providing a body of knowledge that connects vibration patterns with impact on operational machine performance.

Within engineering management, such capability does not exist to extent required for automatic interpretation of performance characteristics. Perhaps stemming from inherent complexity and variability, there is no consistent theoretical basis connecting the activity of individuals within engineering work to impact on performance. Although the existence of numerous CSFs provides a framework of aspects known to be of influence, there remains a lack of consistent tangible
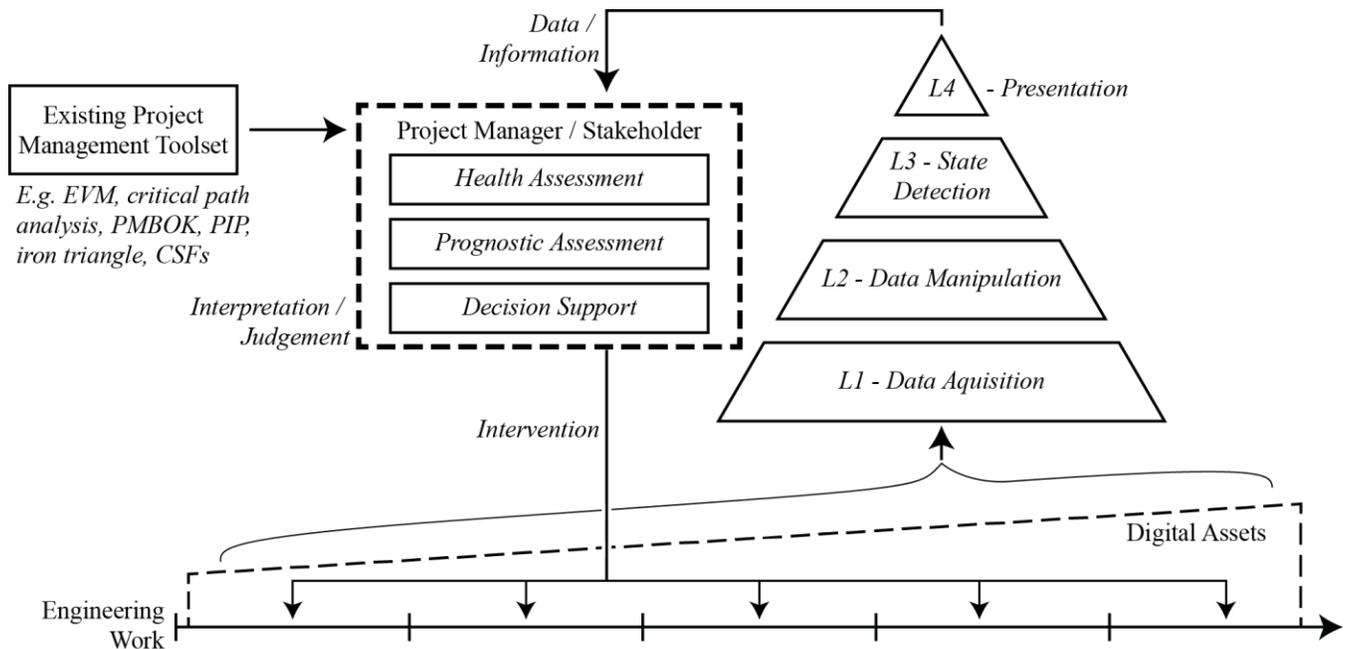
Fig. 2. The EPHM framework, highlighting the central role of the manager in interpretation of analysis.

connection between individual factors and their manifestation in worker activity. For example, while certain generalized guidelines for good practice exist [54], [64], [65], the variance in what constitutes good communication across different project scenarios creates difficulty in interpretation of "good" or "bad" by a machine [66]. As a result, there is currently not capability to, in a general case, automatically interpret engineering activity at the level of performance assessment.

The broad-spectrum activity analysis and pro-active capabilities of IVHM / EPHM can however be enabled through leveraging of the knowledge of managers embedded within the scenario context. By provision of detailed activity analysis directly representing the work under their responsibility, a manager may make judgements through comparison to their own expectation of successful progress. In monitoring of actual activity, a manager can develop specific understanding and be proactive in their intervention and work within the specific context, rather than adhering to general management guidelines and ideals. For example, while open communication pathways are preferred in the general case [54], [67], to which end a manager may attempt to structure their team, understanding of actual activity is needed to determine whether communication patterns are matching those desired, and whether team structure is hence appropriate for the given goals.

In so doing, EPHM aims to rest as supplement and extension of existing management toolsets. Using detailed data analysis, the methods of EPHM generate scenario-specific information that may increase the understanding of managerial workers. As such, information generated provides a directly evidenced description of engineering activity, and may either aid managerial decision-making in and of itself, or may feed into existing managerial toolsets (E.g. earned value management [68], PMBOK [69], iron triangle [26]–[28], CSFs [9]).

In application, EPHM must therefore provide a detailed description of activity from which managerial effort may make

higher-level interpretations of work/scenario state; e.g. CSFs, project performance. This may consist of literal data description of some aspect of activity, and therefore be entirely reliant on managerial interpretation for use, or may be suggestive of its implication through more sophisticated inference towards specific CSFs. Importantly, for the reasons previously discussed, it should in all cases be presented for the interpretation of individuals embedded in the specific context to ensure appropriate judgment of project state is made. This encouragement of evidence-gathering is not unusual within management [30], and forms an underlying assumption of study of success factors – that each should be monitored and assessed within each scenario. The benefit of the EPHM approach is then in provision of methods for assessment, a common ground for study, and generation of a broad evidence-base on which to base managerial decisions.

EPHM aims to provide a support method for those persons working to manage engineering work, allowing monitoring of characteristics that they deem important. This leads to context-specificity, monitoring through consistent forms of activity, and encouraging interpretation and application that is specific to each case. The user-in-the-loop is therefore vital within EPHM, forming the lens through which meaningful understanding is gained.

IV. THE EPHM FRAMEWORK

The complexity of engineering management necessitates significant changes in the application of an IVHM approach to the engineering management domain. Sources of data, while similar in role, are very different in practice. Through reliance on the consistency and predictability of physical principles IVHM is able to automatically interpret and diagnose issues, whereas EPHM requires interpretation by a knowledgeable practitioner. IVHM therefore has capability to form a diagnostic system, while EPHM acts to support and supplement existing

management processes. There is therefore a need for adaptation of the OSA-CBM framework (Fig. 1) for EPHM (see Fig. 2).

Of particular note is the omission of IVHM L4 – L6 in the EPHM implementation of the OSA-CBM framework. As EPHM does not internally infer work state, there is no current capability to automatically diagnose issues or create prognoses. Accordingly, these stages of OSA-CBM are omitted, and EPHM transfers directly from state detection to information presentation, with the contextual understanding of embedded personnel being brought to bare for diagnosis, assessment, and prognosis of future states.

A. L1 – Data Acquisition

L1 within EPHM remains similar to IVHM, with difference concentrated on unit of measurement. With a focus on data collection, L1 senses the literal activity of each actor throughout the project. Data gathering follows a digital approach, ensuring a large evidence base for scrutiny by managers, and enabling application of automatic analysis techniques. In contrast to IVHM, and given the digitalization of engineering processes, there exists the opportunity to monitor activity directly via the digital assets produced. In the context of EPHM these assets can be separated into three classes:

- *Communication:* include all digital communications sent between actors, including email, social network, and instant messaging.
- *Representation:* include all virtual representations and models of the object of the project, including CAD models, virtual prototypes, analysis models (FEA, CFD, etc.).
- *Report / Record:* include all textual or numerical documentation that address the object, process, or project; including technical and managerial reports, presentations, excel spreadsheets, databases, etc.

Each class of digital asset can be monitored at three levels:

- *Physical attributes*: the characteristics of the asset as an entity within the digital system, typically meta-data. E.g. size, creator, creation / modification date, filetype, etc.
- *Content attributes*: the content of the asset. Including, for example, textual data within email communication, numerical data within spreadsheets, coordinate and structural data within CAD models.

TABLE II
POTENTIAL EPHM ANALYSIS METHODS

Class	Attribute	Description	Ref
Comm.	Phys.	**Proxy:** Information availability	[54]
Comm.	Phys.	*Activity* level	[71]
Comm.	Cont.	**Proxy:** Staff sentiment / opinion	[52]
Comm.	Cont.	**Proxy:** User authority	[81]
Comm.	Cont.	**Proxy:** Modes of working	[82]
Report	Phys.	**Proxy:** Process complexity	[83]
Report	Phys.	*Activity* focus / sequence	[84]
Rep.	Phys.	*Activity* / System dependency	[76]
Rep.	Phys.	*Activity* level [filetype]	[85]
Rep.	Phys.	*Activity* focus	[85]
Rep.	Phys.	**Proxy:** User Competency	[86]

- *Context attributes*: the use of the asset within the wider project socio-technical system. For example, the department or team of origin, the stage within the project process, or asset authority or maturity.

The opportunity to analyze data according to each attribute of each class of asset provides a broad source of existing evidence for all analyses.

B. L2 – Data Manipulation

As data gathered during L1 represents all digital assets produced during the activity of actors, its properties represent and are a product of the activity in which it was generated.

The role of L2 is two-fold. First, as the primary and more sophisticated analyses are performed within L3, L2 must transform raw data into the inputs required.

Second, as activity forms the common unit of measurement from which more sophisticated analyses are implemented, there is potential for single data sources to be used in multiple ways and, as such, the use of common associations with activity enable potential for greater standardization across analysis methods. Through cross-association of separate analyses, for example as in relation to requirements gathering, there is potential for further analyses to be built on a common ground, with integration of multiple data sources that share similar representations, or broader aggregation across multiple activity areas.

C. L3 – State Detection

Within L3, analysis takes the inputs provided within L2 and presents them in a meaningful form given the work context.

There are two forms of analysis that may be employed. Firstly, all activity data produced through L2 may be studied directly through statistical means, where benefit may come from association of current state with past states, historical cases, and trends with time. Through knowledge of the typical profile for a given scenario, formed by a manager's expectation or historical data analysis, alerts can be raised should specific areas of activity exhibit unexpected or abnormal behaviors. For example, a large increase of communication levels may indicate occurrence and attempted resolution of an issue. Representation of activity forms the most basic analysis of L3, in which meaning must be assigned and judged by the user. Several analyses linked to the digital assets to which they are applied are given in Table 2.

Second, through more sophisticated analysis methods, some performance-affecting factors can be studied more directly. This is referred to as *proxy generation*, where the output is a direct interpretation of a CSF. While few analysis methods have been developed directly for the EPHM approach, there are many in existence within other fields that are applicable. For example, file creation and modification dates (*representation class, physical attribute*) can, once manipulated and analyzed, describe level of activity and progress rate, with further examples given in Table 2. Generation of proxies for important areas of engineering work provide a direct measure to a manager, forming an evidence-base for their decision-making processes.

In practice the implementation of a full EPHM approach will likely be a large and bespoke operation, as with IVHM, in which suitable analyses are identified. In particular, difference is expected in analytics as applied to project or operational engineering scenarios, in that the former may look for patterns associated with individual project stage, while the latter may look for patterns indicating deviation from steady or longer-term activity states consequent from operational scenarios. There is benefit even in lower levels of implementation, applying subsets of analysis techniques in areas that are thought to be of higher importance in the specific context. Additionally, as analysis methods are applied to input data that is common across many engineering scenarios, there is scope for some level of standardization.

D. L4 – Presentation

EPHM places responsibility on the interpretation of the manager, providing an evidence base for their investigation and subsequent action. It is therefore vital that data presentation is considered carefully.

While appropriateness of presentation method is largely dependent on data itself [70], understanding can be supported through contextualization to the specific context and scenario. Comparison and presentation of results with existing norms and threshold values provide a quick reference of the aspects of the current activity that are atypical. Presentation of all outputs in relation to time and project timeline create a relation to project process. Separation of results according to project areas, such as *person, process, product, project*, encourages breadth in classification of performance. Where good and bad states are known, such as may be the case for proxies once generated, visualizations such as traffic light systems [70] provide quick understanding of suitable performance. In all cases, presenting data through a tangible connection to the engineering scenario may ease interpretation for the manager.

The formation of appropriate presentation regimes is bespoke, as are the visualization methods that are suitable in each case, but it is vital that sufficient attention is given to the manner in which a manager interrogates data, and how they can be supported in understanding efficiently.

E. L5 – Health Assessment

It is important to note that EPHM is not proposed herein as replacement for managerial tools currently available, but rather as a supplementary evidence-base for context-specific interrogation and decision making. Given their own understanding of the work, its timeline and schedule, requirements, budget etc., a manager may use detailed understanding of actual activity to judge the state in comparison to their expectation of high performance.

Due to the situated and contextual individuality of engineering projects it is currently impossible to produce, verify, and validate generalized models for prognostics. This also remains a challenge in IVHM, despite consistency in the physical principles that govern mechanical systems, and is exacerbated by the lack of consistent rules governing appropriate action in varying management scenarios.

In contrast to structuring of engineering work according to generalized CSFs, EPHM allows assessment in the specific case, judgment of the actual effectiveness of structures given the effect on activity, and intervention when deemed necessary. The skill of the manager is therefore paramount, where their interpretation and understanding of the context in which they are embedded drives the effectiveness of the interventions that they may make. Accordingly, EPHM does not directly include stages equivalent to L4, L5 and L6 from IVHM, in which the system automatically performs interpretation and recommends action. Within EPHM, these steps are performed by the manager, based on their understanding of the scenario and the data.

V. EPHM IN APPLICATION

This section presents four cases of analysis and interpretation, detailing the processes and analyses within each level of the EPHM framework for each. All examples show analyses presented in publications elsewhere, and are here summarized only. Presentation is in reality highly bespoke and tailored for the individual case, with examples here provided. Stage L3: *State Detection* includes analyses that interpret *activity* directly, or **proxies** that imply the state of CSFs.

A. Case One – Activity from Email Communication

This analysis automatically extracts the areas on which workers are focusing throughout a project, and the levels of activity associated with each [71], and is based on the field of study of information diffusion [54], [72]. In the original work, analysis occurred on 10,396 emails from a 4-year project.

L1 – Data Acquisition: Data includes textual content, to/from, and timestamp of email communication (asset class: *Communication*; attribute: *Content* and *Physical*).

L2 – Data Manipulation: Topics of discussion extracted from textual content using *tf-cidf* technique, see [72]. Level of activity detected through frequency of emails transmitted that discuss each topic, compared to historical norms.

L3 – State Detection: i) *Activity:* Level of discussion over project lifespan, for each topic area. ii) *Activity:* High and low levels of relative discussion highlighted with respect to historical usage. iii) *Activity:* Key topic areas within each project process stage listed, based on level of discussion.

L4 – Presentation: Key topics for each stage presented directly. Activity / discussion levels graphed individually for each topic, highlighting of areas of high discussion.

L5 – Health Assessment: Providing a real-time elicitation of the subjects of working and associated activity level, judgement can be made of progress, work focus of engineers, or priority. Cases of abnormally high or low activity may indicate concentrated effort to remedy issues, abnormally low levels may indicate delays in an area or diminishing priority, and the appearance of topics that are atypical for the project or stage may indicate scope change / creep.

B. Case Two – Project complexity

This analysis studies the type and sequence of activities occurring within multiple short-term repair projects, extracted
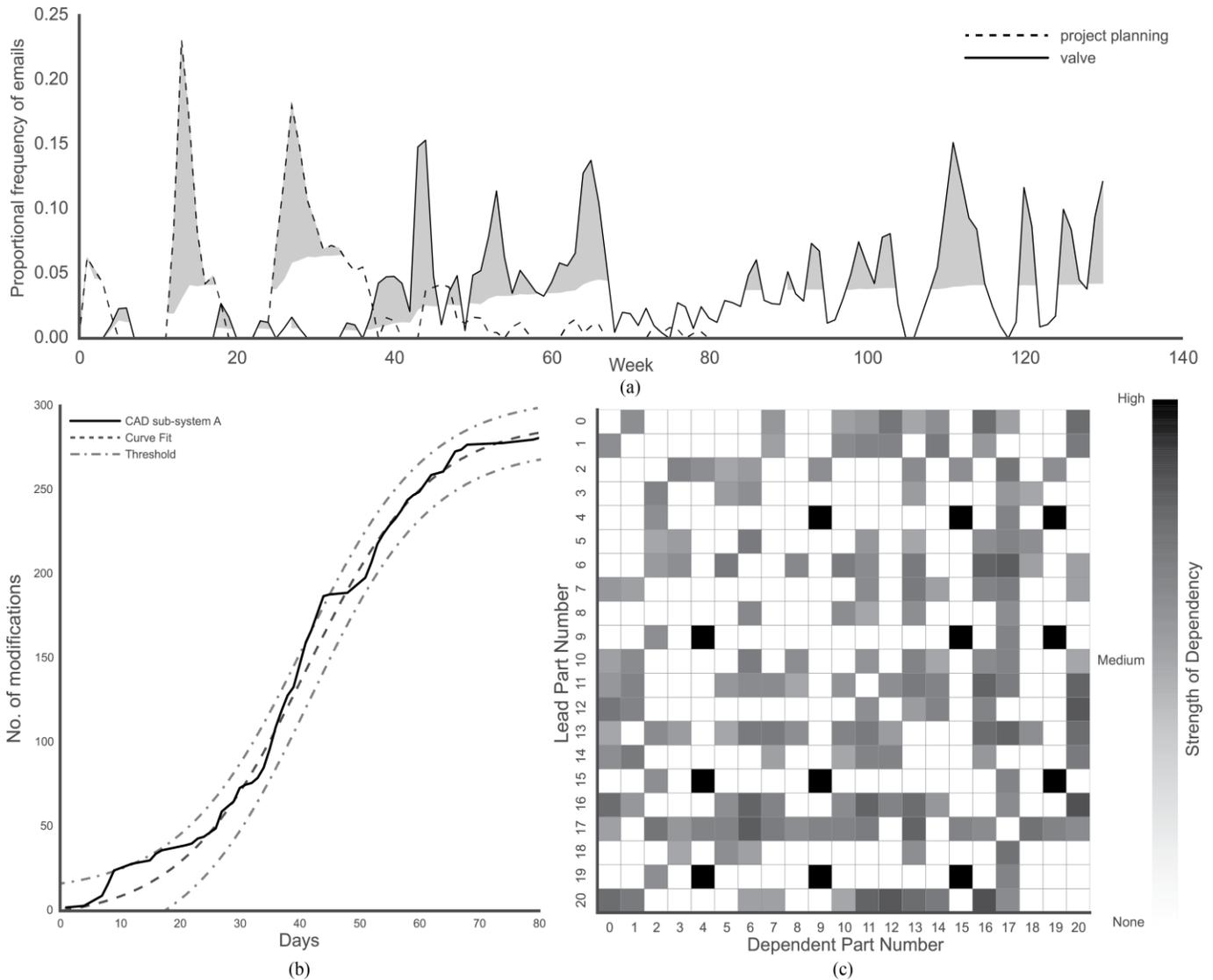
Fig. 3. (a) Case 1 - Topics and associated activity discussion rates throughout a project. Shaded areas indicate relative high levels of activity. Note evidence of high discussion and periodicity for "project planning" in early stage, consistent effort throughout with peak in later-stage for "valve". (b) Case 3 – S-curve showing predicted time-to-completion for CAD assembly. Prediction stabilizes at 50% completion. (c) Case 4 – System dependency and modularity adjacency matrix. Individual squares represent dependency between CAD files, where darker indicates higher strength of relationship.

automatically from project documentation. Activity sequences are analyzed to infer project complexity and time-to-complete. In the original work, the analysis is applied to 396 reports, each from one type of project within a single large aeronautics company.

L1 – Data Acquisition: Data includes content and meta-data of engineer-submitted project documentation (asset class: *record*; attribute: *content* and *physical*).

L2 – Data Manipulation: Activity type inferred from document content – project reports consist of collation of project documentation. Transactional activities extracted by information request documentation. Activity sequence extracted from document time-stamp.

L3 – State Detection: i) **Proxy:** Project complexity inferred from ratio of internal/external information requests, approach validated by project workers. ii) *Activity:* Time-to-completion inferred through sequence analysis of activities within project timeline. Machine learning of relation between activity

sequence and project length allows prediction based on pattern appearance.

L4 – Presentation: Expected project complexity presented directly. Time-to-completion presented numerically or graphically for each.

L5 – Health Assessment: Higher complexity in a project may be indicative of a need for higher managerial attention, higher resource, or higher employee experience and skill. Through automatic classification a manager is given scope to prioritize resource allocation etc. to ensure best utilization. Time-to-complete provides scheduling support for future planning.

C. Case Three – Time-to-completion of design work

This analysis studies the relationship between CAD file creation / modification rate and design progression, and predicts time-to-completion of individual components and sub-systems. In the original work, the analysis is applied to a single car-development project, consisting of 892 files [73].

L1 – Data Acquisition: Creation and modification dates of all CAD and Analysis files produced during design process (asset class: *representation;* attribute: *physical*).

L2 – Data Manipulation: Rate of file creation and modification extracted, describing level and rate of interaction between engineer and design output.

L3 – State Detection: Activity: Activity level, design progress rate, and time-to-complete determined through modelling of data against S-curve.

L4 – Presentation: Design progress rate and time to complete presented numerically or graphically.

L5 – Health Assessment: Prediction of time-to-completion with activity level provides scheduling information, and areas of focus of work. This clarifies actual work rates, worker priorities, and allows, for example, reallocation of resource should time-to-complete be judged to extend beyond acceptable limits.

D. Case Four – Process and product dependency

This analysis studies the interdependency between systems designed during the project, allowing understanding of overall complexity and likelihood of rework following design changes. This work is based within the extensive field of Design Structure Matrices [74], [75]. In the original work, the analysis is applied to a single car development project, consisting of 1,432 files with 10,145 updates [76].

L1 – Data Acquisition: Creation and modification dates of all CAD and Analysis files produced during design process (asset class: r*epresentation;* attribute: *physical*).

L2 – Data Manipulation: Formation and monitoring of cascade of file modifications, i.e. when work occurs on one asset, which other files typically receive consequent effort.

L3 – State Detection: i) **Proxy:** Network of system dependency. ii) **Proxy:** Modularization of system components and activity sequences; i.e. map of potential dependency impact of a change to a single component or sub-system.

L4 – Presentation: Connected systems presented as individual modules within adjacency matrix or project model, with likely impact and associated risk of rework associated with design changes.

L5 – Health Assessment: When a system contains many dependent elements there is a higher potential for change propagation and rework [77], [78]. Measuring inter-reliance by activity carried out allows a manager to assess the impact of potential design changes. This allows prioritization of areas in which change propagation would have a significant impact, prediction of likely time-to-complete following design change, and deeper understanding of the modularity and cross-team impact of activity – i.e. clarifying the impact of a delay in one team on others further downstream.

E. EPHM Analysis

These four cases demonstrate the fundamental EPHM approach, in which low-level data is automatically extracted from the digital outputs of engineering activity and transformed into representations of activity or the engineering scenario. All cases described can be automated and applied in real-time,

therefore generating useful analyses for interpretation by a manager. None, however, suggest action in themselves, instead relying on interpretation of outputs as normal, atypical, good, or unsatisfactory. In this way they provide evidence to support decision-making processes.

A key strength of EPHM is in potential for complementary analysis generating emergent understanding. As the medium through which engineering work is implemented, activity is embedded with the characteristics of work/scenario in which activity occurred. It therefore follows that, should some aspect be unsatisfactory, opportunity exists for detection through the manifest impact on the activity that engineers perform. As a result, engineer activity is replete with opportunities for simultaneous analysis from similar inputs. Within Cases 3 and 4, for example, monitoring of CAD model creation data allows understanding of product-centric (system dependency and modularity), and process-centric (activity dependency) understanding. Further, it is contended that through combination of multiple analysis within a single scenario, there is significant scope for generation of broad understanding.

VI. Conclusions and Further Work

Due to inherent context-sensitivity, and commensurate difficulty in formation of direct methods of measurement, the effective monitoring and assessment of engineering work possess a significant and unresolved challenge. This paper has presented an approach that attempts to mitigate the sole reliance on high-level generalizations of management structures that in theory induce "good" and "bad" performance through utilization of broad-spectrum activity data, automatically extracted from the digital assets produced as every-day artefacts of engineering processes. Correspondingly, this work presents an approach for formation of an evidence-base for engineering managers, utilized for decision support and intervention grounded directly in the specific work/scenario context. The approach, termed *Engineering Project Health Monitoring* (EPHM), is therefore intended not to interpret performance, nor to directly suggest actions, interventions, or structures that should be applied to the project, but rather to provide information in support of the decisions and processes already affected, reduce managerial investigative effort, and enable detailed understanding of the current engineering scenario. As such, it's capabilities support and supplement existing managerial knowledge and processes through significant extension to scenario-specific managerial understanding; information upon on which decisions are made.

EPHM draw from the established *Integrated Vehicle Health Monitoring* (IVHM) approach for assessment and proactive maintenance of mechanical systems. Facing similar issues in variety of the object of study and complexity in analysis, IVHM provides strong evidence of the capability of such a system in generation of detailed understanding and prevention of future issues. While significant adaptation has been required, the EPHM approach affords similar potential benefits, allowing monitoring and assessment with sensitivity to the influence of

context and situated variation in importance of individual elements upon project/operational performance.

In taking a bottom-up approach, EPHM replaces the challenge of identifying and applying appropriate CSFs with that of identifying appropriate analysis methods. This is met through the expertise of the user, who is embedded within the work context, using detailed and focused analysis methods to provide guidance towards areas they believe to be influential. While different forms of analysis will be of varying value, all provide direct interpretation of the activity and situation, many in real-time. As a result, all have potential to directly support the investigative effort of the manager. Key within EPHM is therefore the application of context-neutral analysis, with scenario-specific interpretation enabled by the experience of users.

As EPHM uses digital assets and activity as units of measurement there is scope for standardized analysis, in contrast to the reliance on managerial understanding currently propsoed. With digital assets and activity as common units of measurement, such standardization may provide a suite of effective analyses that are more broadly applicable, and are less reliant on managerial experience for effectiveness. There is a significant need however, both to ends of standardization and for general implementation, for much development of analysis methods. Many examples of relevant methods to study activity are present in literature, but a significant task resides in their collation and adaptation to the point that they can be implemented within an active EPHM system. A number of these are given in Table 2. Further to this, there may be some consistency in those analyses and information that prove to be more useful to managerial processes. In identifying such, it may be possible to develop a baseline capability of EPHM that generates useful understanding with lower levels of bespoke system development. This would require detailed application across several scenarios and discussion with participating managers, and remains a significant area for further work.

While the potential usefulness of an EPHM approach is demonstrated within Section V, there remains no full test of an EPHM system. Individual analyses provide individual understanding and hence, while some combination can be seen and hypothesized, there is a need for development of a holistic system within a single context to fully understand the scope of possible benefits.

The EPHM approach provides potential for consistency in application across engineering, while ensuring interpretation and actions are specific to the context under study. Through detailed and low-level data, automatically gathered and analyzed in real-time, it attempts to provide detailed information to engineering managers, supporting their decision-making processes. While there is much scope for future development, this paper presents the fundamental concepts, and demonstrates fundamental viability and potential utility of the approach, generating high-level actionable information directly from low-level activity data.

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