Engineering Project Health Management: A Computational Approach for Project Management Support Through Analytics of Digital Engineering Activity

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Abstract—Due to the situational and contextual individuality of engineering work, the in-progress monitoring and assessment of those factors that contribute to the success and performance in a given scenario poses a distinct and unresolved challenge, with heavy reliance on managerial skill and interpretation. Termined 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 the 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 the 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 an engineering activity and a 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, integrated vehicle health management (IVHM), project management, process monitoring and control, project performance, project success factors.

I. INTRODUCTION

IN CONCERT with the globalization and driven by the development age, the 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 toward the measurement and monitoring of the 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, modeling, 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 a success are highly variable. As a result, the attainment of an ideal formed from top–down analysis of the success requires careful consideration in its applicability.

This leads to the problem statement of this paper. As unique and context-dependent entities, the management and success of an engineering work requires individual and distinct analysis and domain understanding. Whereas the literature presents a synthesized generalization of factors for the success, it is challenging to determine the importance and impact of each for every unique scenario.

To support such management challenges, this paper proposes an approach to the 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 the engineering activity, and the processes by which such information may be used to affect informed and context-applicable decision making.

Through utilization of a low-level data extracted from the in-operation characteristics of a system and in-built knowledge...
of system working principles, IVHM generates diagnoses and
diagnoses of current and the future system performance au-
tomatically, 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 the project
health.

The remainder of this paper is organized as follows. Section II
presents a literature review of metrics of assessment of engi-
nering projects and operations, and of the approach of IVHM.
Section III presents an adaptation of IVHM to the engineering
management. Section IV presents four distinct cases of analyses
following the IVHM approach. Section V presents four cases of
analysis and interpretation, each detailing the processes and
analyses within the levels of the EPHM framework. Section VI
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 the extant literature, and
their application to context-specific engineering scenarios. Fol-
lowing, it presents and reviews the approach of IVHM, includ-
ing 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 the engineering work progress and judg-
ment 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 per-
formance indicators (KPIs) have been proposed to form the
benchmark by which a manager can judge the success of an
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 ap-
provals of internal and external stakeholders such as company
and end-user [16], [27]. Determination of such KPIs can hold a
significant challenge, with a potential for variation and an ab-
stract relationship between an actual activity and impact on KPIs
under scrutiny [27], leading to reliance on estimation. As such,
significant managerial challenge exists in the measurement of
the performance or the 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 the literature. In [29], 53 factors for project
success in software development ranging from the corporate
environment to technology are presented; in [30], ten over-
arching factors associated with failure across general project
management are presented; in [31], 88 factors known to influ-
ence the project performance in engineering projects are pre-
sented; and in [9], 12 CSFs based on interview within 70 or-
organizations are presented. Illustrated by this breadth, there is
recognition that the influencers of the project success across
scenarios have 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 prac-
tice, 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], complex-
ity [33], [34], scope [35], and capability [36], [37] and, given
high potential for variation between scenarios, it is unsurpris-
ing 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 the 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 the performance (KPIs) and that
which may affect the success (CSFs), a need exists to aid man-
agers in their detailed understanding of the specific work and
activities under their responsibility. Where the existing litera-
ture provides ample framework by which the project success
or state may be measured, it also highlights the need for a
detailed understanding of the specific state on a per-case ba-
sis. 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 man-
gerarial 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 a particular progress
in the 2010s [22], [23], [43], IVHM is focused on the infer-
ence of high-level understanding of the machine performance
from low-level operational data. Aiming for autonomy in ma-
chine diagnosis and prognosis, IVHM uses high levels of em-
bedded sensor capability and knowledge of underlying opera-
tional principles to predict specific mechanical issues from early
warning signs, such as vibration profiles characteristic of high
wear coupled with a high temperature in a specific component.
Through broad spectrum and combinatory data analysis, IVHM
aims to allow prediction of the need for the maintenance inter-
vention before the performance is affected beyond acceptable
levels.

In implementation, IVHM frequently employs the open
system architecture–condition-based monitoring (OSA-CBM)
The key purpose of IVHM is in the analysis of complex and unique machines, to interpret the performance in a manner appropriate to the specific machine, and to detect and predict machine-specific problems. IVHM is thus targeted toward similar issues to those faced in the engineering management—individuality of that under study, difficulty in assessment, and a monitoring of a large quantity of variables that may affect the activity and the 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 the engineering management to be addressed, the presentation of which forms the purpose of this paper.

Through a low-level, algorithmically interpreted evidence base, IVHM encourages direct measurement and monitoring of trends-in-progress, subsequently inferring the activity, performance, and issue through comparison with an underlying knowledge base. Accordingly, this paper explores the adaptation and application of an IVHM methodology to the discipline of the engineering project management, termed engineering project health management (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 works are 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 a sensor output compared to a knowledge base derived from functional, behavioral, and structural understanding of the 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 nondesired, EPHM must monitor the in-progress activity of an 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 a near-real-time analysis of the 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 the 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 an actual activity within the machine, with broad analysis selected to capture all aspects of the 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 the machine activity allow higher level inference of the state of the wider system.

Direct similarity may be drawn in an 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, the 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 the machine activity in IVHM allows interpretation of a higher level system health, this relationship between the work/scenario characteristic and the engineer activity inherently links low-level activity and higher level interpretation of the project health. As an example, properties of an 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 relationship to project success [15], [55]–[60]. While less tangible in the engineering management context than the machine of IVHM, the existence of such a 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 an 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 an 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.
The broad-spectrum activity analysis and proactive 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 analyses describing the ongoing work for which they are responsible, a manager may make judgments 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 an open 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 an activity from which a 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 toward 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 an evidence gathering is not unusual within a 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. EPHM FRAMEWORK

The complexity of the 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, whereas EPHM acts to support and supplement existing management processes. There is therefore a need for adaptation of the OSA-CBM framework (see 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 prognosis. 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 the following three classes.

1) **Communication:** It includes all digital communications sent between actors, including e-mail, social network, and instant messaging.

2) **Representation:** All virtual representations and models of the object of the project, including computer aided design (CAD) models, virtual prototypes, analysis models (finite element analysis (FEA), computational fluid dynamics (CFD), etc.).

3) **Report/Record:** All textual or numerical documentations 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 the following three levels.

1) **Physical attributes:** The characteristics of the asset as an entity within the digital system, typically metadata, e.g., size, creator, creation/modification date, filetype, etc.

2) **Content attributes:** The content of the asset. Including, for example, textual data within e-mail communication, numerical data within spreadsheets, coordinate and structural data within CAD models.

3) **Context attributes:** The use of the asset within the wider project sociotechnical system. For example, the department or team of origin, the stage within the project process, or asset authority or maturity.

The opportunity to analyze the 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 the 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 twofold. 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 a 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. First, 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 II.

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 II. 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.

<table>
<thead>
<tr>
<th>Class</th>
<th>Attribute</th>
<th>Description</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comm.</td>
<td>Phys.</td>
<td>Proxy: Information availability</td>
<td>[54]</td>
</tr>
<tr>
<td>Comm.</td>
<td>Phys.</td>
<td>Activity level</td>
<td>[71]</td>
</tr>
<tr>
<td>Comm.</td>
<td>Cont.</td>
<td>Proxy: Staff sentiment / opinion</td>
<td>[52]</td>
</tr>
<tr>
<td>Report</td>
<td>Phys.</td>
<td>Proxy: Modes of working</td>
<td>[82]</td>
</tr>
<tr>
<td>Rep.</td>
<td>Phys.</td>
<td>Activity level [filetype]</td>
<td>[85]</td>
</tr>
</tbody>
</table>
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. In addition, as analysis methods are applied to input data that is common across many engineering scenarios, there is a 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 creates a relation to project process. Separation of results according to project areas, such as person, process, product, and project, encourages breadth in classification of the 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 a 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 the actual activity to judge the state in comparison to their expectation of the 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 E-mail 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 e-mails from a four-year project.

L1—Data acquisition: Data includes textual content, to/from, and timestamp of e-mail 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 e-mails transmitted that discuss each topic, compared to historical norms.

L3—State detection: 1) Activity: Level of discussion over project lifespan, for each topic area. 2) Activity: High and low levels of relative discussion highlighted with respect to historical usage. 3) 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, judgment 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 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 metadata 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 collection of project documentation. Transactional activities extracted by information request documentation. Activity sequence extracted from document time-stamp.

L3—State detection: 1) Proxy: Project complexity inferred from ratio of internal/external information requests, approach validated by project workers. 2) 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 subsystems. In the original work, the analysis is applied to a single car-development project, consisting of 892 files [73].
**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 paper 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 1432 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: 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 modeling 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.

**E. EPHM Analysis**

These four cases demonstrate the fundamental EPHM approach, in which low-level data are 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 a 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. Conclusion 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 artifacts of engineering processes. Correspondingly, this paper 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, its capabilities support and supplement existing managerial knowledge and processes through significant extension to scenario-specific managerial understanding; information 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 toward 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 proposed. 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 II. 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 the 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.

REFERENCES


Authors’ photographs and biographies not available at the time of publication.