Tools for HUMS Exploitation

CJ Hockley[1], A Zagorecki[1], A Duncan[1], KR McNaught[1], K Wand[1]
[1]*Cranfield University, Shrivenham, SN6 8AL,*
E-mail: c.hockley@cranfield.ac.uk

Abstract

During 2009-12 Cranfield University at the Defence Academy at Shrivenham has been involved as one of several universities in a research programme supported by the Engineering Physical Sciences Research Council (EPSRC). The work has focussed initially on military equipment and in particular using data from HUMS in order to exploit the benefits it can deliver. Three separate tools have been developed aimed at improving the ability to leverage value from HUMS to improve availability and create maintenance efficiencies. The paper describes the tools that are now developed. They are a HUMS Cost Benefit tool for land vehicles, a Failure and Degradation Elicitation Support (FADES) tool and a Predictive Maintenance Probabilistic Decision Support (PMPDS) tool. The paper reviews the background to the development of these tools and describes their utility. The current use of the tools is described using a case study of a current application.

Keywords: predictive maintenance, prognostics, cost benefits, decision support, maintenance efficiency.

Introduction

Cranfield University at the Defence Academy at Shrivenham was granted a 3 year research contract as part of a consortium of several universities in a programme funded by the Engineering Physical Sciences Research Council (EPSRC). It was an outcome of a previous larger consortium of University research call for Support Service Solutions: Strategy and Transition (S4T) which sought to establish an academic focus that informed and led the continued transformation of the UK economy towards increasing value generation from product related services. Details of the research outputs of S4T are available in a book which published some of the background and results [1]. Cranfield University at the Defence Academy concentrated their part of the S4T research on HUMS and the ability to deliver Predictive Maintenance. The S4T project then enabled a smaller consortium of Universities to bid for a follow-up EPSRC research contract which was aimed at developing practical tools from the S4T research. The new research contract was called Knowledge Transfer Box (of tools) – KT-Box [2]. The research produced over 50 tools and mini-tools from the 6 Universities involved; the tools developed at Cranfield University's Shrivenham campus focussed initially on military equipment and in particular the use of data from HUMS in order to exploit its benefits. These particularly include the ability to leverage value from HUMS to improve availability and create maintenance efficiencies.

The paper describes three tools that are now developed starting with a HUMS Cost Benefit tool for land vehicles [3]. This tool does not produce answers in pounds or dollars; rather it identifies relative benefits, but would allow the user to allocate particular costs if necessary. The other two tools involve taking HUMS data and enabling decisions to be made that improve availability and maintenance efficiency. The first of these tools is called the Failure and Degradation Elicitation Support (FADES) and covers knowledge elicitation at the component level for specific components of interest, or those that have been identified as critical [4]. The third tool, Predictive Maintenance Probabilistic Decision Support (PMPDS) takes inputs from HUMS and FADES in order to provide decision support for predictive maintenance planning [5]. The paper reviews the background to the creation of these tools and describes both their principles and their utility. The current use of two of the tools will be described using a case study.

HUMS Cost Benefit Tool

The aim was to create a tool to assess the through-life cost-benefits of Health and Usage Monitoring Systems (HUMS) and Systems Information Exploitation (SIE) in the military land environment. Since 2003 when the UK MOD decided that adopting HUMS was a good thing for land vehicles, little actual progress has been made. One of the major factors has been the lack of a tool to allow acquisition authorities to quantify the benefits of HUMS/SIE in the land environment.

The aim of the tool was thus:

- To create a step change increase in adoption rates of HUMS and provide a tool that would show whether benefits could be realised.

The tool needed a limited input load in order to extract high level outputs within a package that could be used on any MoD computer and thus be used by any project team. This drove the team to consider only an Excel Spreadsheet based tool.

The starting point for tool development was to research the benefits that have been realised in both air and commercial land environments and to translate them to the military land environment. In addition to this activity a number of previous HUMS benefit tools were analysed in order to understand the problem space (for example the DSTO Humsave tool). Complementary academic research was also reviewed. From this research it became clear that the models previously developed relied largely on assumed costs and that true costs for running and maintaining the vehicle fleets were unlikely to be available and particularly in the military land environment. Consequently there was a need to develop a map of benefits and their relationship with the costs within the system and to use this as the basis of the tool. The initial benefits map was in essence developed from brain-storming with various experts and continually refined before being developed into a final benefits map that would form the basis of the tool input and assessment sheets. This was achieved by a number of SME reviews and workshops. The tool was then developed using a QFD analysis process.

The tool consists of an Excel workbook detailing the process required to conduct a cost/benefit analysis of the implementation of HUMS/SIE in land vehicles and an Excel spreadsheet model that is used to conduct the quantitative part of the analysis. This model considers costs at a high level and is written in a generic way to enable it to be used for any vehicle. It considers through-life costs and benefits across all Defence Lines of Development (DLODs) in terms of both CDEL and RDEL[1]. The workbook gives a list of factors that need to be considered when conducting an analysis of utilising HUMS/SIE on a specific fleet of vehicles. The spreadsheet allows a high-level quantitative analysis to be created and is

[1] **Capital DEL (CDEL)** – New investment in equipment and infrastructure that has a life over more than one financial year e.g. ships, buildings and aircraft.
Resource DEL (RDEL) – Current expenditure such as pay, allowances, and running costs. It also includes the indirect costs of ownership of assets such as depreciation.

written generically to make its use as flexible as possible. It has a number of sheets which the user first enters data into the Fleet data Input Sheet which contains general inputs such as whether the fleet of vehicles considered is to be new or legacy vehicles and the numbers of years in service to be considered, the amount of HUMs equipment that will be needed and the level of fitting effort required. In order to allow unbiased assessment of HUMS systems no particular HUMS solution is selectable but a number of possible parameters to be monitored are provided in order to build up an 'ideal' system or to select those parameters that have been offered to the user by a manufacturer. Up to two systems can be compared at any one time enabling current and 'upgrades' or two build options to be considered. The next sheet is the Data vs Intermediate Effects Sheet. It consists of a matrix where HUMS parameters selected to be monitored are compared to intermediate benefits. The term intermediate benefit was defined as a beneficial effect realised through having monitored the parameter but that is not an end benefit in its own right. These then feed into the final benefits. The size of the effect was then assessed using the QFD logic with a scale from -9 to 9 where 0 indicates no change from the current situation, negative indicates a detrimental effect (eg increased workload) and positive indicates a true benefit. The selection of data options in the previous Fleet Data Input Sheet results in the scores from this sheet to be either used in the totals or removed from the totals to be taken through to the next sheet. This is where Intermediate Effects are compared to Final Effects. Again the sheet is a matrix with a list of identified intermediate benefits from the previous sheet compared to final effects or benefits. A score is given to the effect of the intermediate benefit on the final benefit using the same QFD scoring system. In the next sheet the Final Effects are compared to the DLODs. Here_there is an assessment of where the final effect or benefit (positive or negative) will be realised, either in the CDEL or RDEL time frames within the DLOD framework. Again the same QFD scoring is used as in previous sheets however whilst actual costs are again not considered here, this sheet is easiest to consider in terms of whether the benefit will increase or decrease spending within the two time frames. This sheet then feeds the graphical outputs to provide reports. In the next Cost Drivers Sheet, there is a refined list of costs associated with fitting HUMS/SIE which is then assessed against the same DLOD RDEL and CDEL headings as the Final Effects vs DLODs Sheet and is populated via an SME judgement panel; the answers to the questions on first fleet data input sheet drive which costs are counted from this sheet. The output of this sheet feeds the report sheet which displays a copy of the answers to the questions on the fleet data input sheet for reference and then displays the benefits and costs as comparisons if two sets of data were chosen in the input sheet or as a comparison to the "do nothing" option.

The model was constructed and beta tested by the team with assistance from the MoD user community initially in April and then subsequently in September. In addition to this a member of the team attended a placement with Supacat (Devon UK) to perform a case study using the tool in order to assess its usefulness to the industries providing equipment to the UK MoD. The interface of the tool is user-friendly. However the tool performs at its best when used with analyst support since the outputs need to be considered carefully to maximise the benefit to the user community. The use of the tool is intuitive however the outputs need to be considered carefully to maximise the benefit to the user community. The tool lends itself particularly to the assessment of a number of options as the graphical outputs are comparative in nature. The tool is useful for both new and legacy fits however in the case of legacy fits it should be used with caution and the cost and time required to fit new sensors should not be underestimated. The tool assumes that the systems on board legacy vehicles are compatible with the upgrade kits and while there may be data available this may not be sufficient to get meaningful outputs within the HUMS domain. There is a need for a level of SME input to get the best out of the tool however this input is largely a tailoring of the pre-set scores for individual projects and so does not require an overly burdensome process. The tool also provides a useful discussion platform for the team to both test the effect of the collection of individual parameters and ensure all the relevant benefits have been considered within the project planning phase. The feedback from the users has been extremely positive to date and whilst not able to provide hard cost data the tool provides an excellent graphical display of where benefits may be realised through the fitment of HUMS to military land platforms.

Failure and Degradation Elicitation Support (FADES) Tool

The Failure and Degradation Elicitation Support (FADES) tool is intended to improve maintenance effectiveness and service provision by providing a software platform for elicitation, structuring, and sharing of engineering and maintenance personnel's tacit knowledge. It is intended to augment the capabilities of intelligent usage data collection on modern complex engineering systems. Health and Usage Monitoring Systems (HUMS) provide valuable usage and failure data but this data by itself is insufficient to provide all the information required to develop cost-effective prognostic systems which deliver a predictive maintenance capability. However, personnel responsible for planning and conducting maintenance acquire much knowledge regarding failure modes, degradation mechanisms and actual condition of the equipment in the course of their work. FADES is an elicitation support tool that aims to ensure that this knowledge is properly collected, collated, and exploited.
The benefits that are expected from the use of the tool include, but are not limited to:

- Improvement in automated prognostic maintenance systems by incorporating knowledge and experience elicited from maintenance personnel.
- Creation of a database of information specifically relevant to prognostic applications, including component reliability, maintenance actions and failure patterns.
- Enabling the collection and use of knowledge from a larger number of personnel involved in maintenance processes than is currently feasible.

The FADES software supports the collection of tacit knowledge necessary to implement effective prognostic systems. It provides a method of eliciting and formalising knowledge from human experience and encoding it in a structured, digital form. The resulting database can be used throughout a support organisation to support maintenance activities. The tool is in the form of a prototype of the elicitation software (with an optional database infrastructure), supplemented by a supporting user guide on the elicitation approach.

The FADES tool provides a well-structured and formalised method to understand the maintenance needs of a platform viewed from various perspectives. It enables:

- Insight to be gained into opportunities that arise from the exploitation of predictive maintenance.
- Sharing of knowledge between various teams with the organisation (or even between organisations) in particular for instance between the service engineers and the maintenance personnel or between operational support staff and support contactors.

The FADES software is only a part of the solution. To take full advantage of the approach developed, the organisation should be prepared to commit some effort to customise the FADES approach to particular requirements and needs. Figure 1 presents which aspects of the FADES tool are ready as off-the-shelf products, and which should be customised to a particular application.

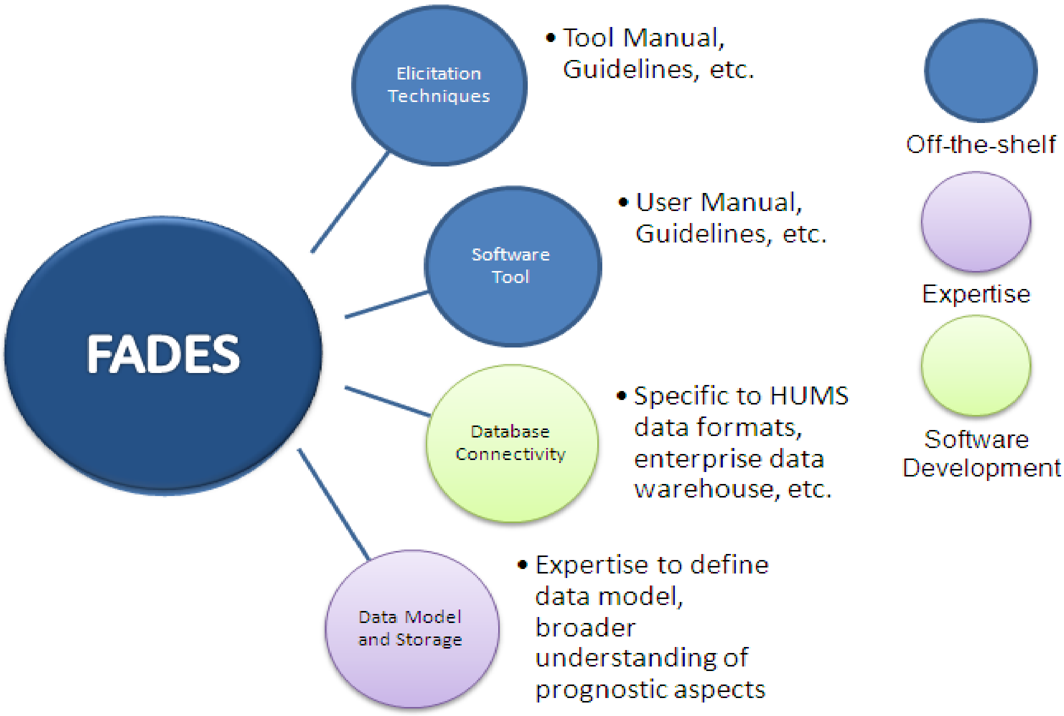

Figure 1. FADES Tool Structure

The FADES tool offers a comprehensive and consistent approach to knowledge elicitation which is specifically designed to fit the needs of prognostic modelling for the purpose of exploiting HUMS and organisational knowledge, to deliver improved maintenance, and consequently improved service provision. To fully exploit the potential of the FADES approach, even if it is not strictly necessary, an organisation should integrate FADES with its existing databases to streamline the FADES model building process by, for example: extracting component databases, linking to maintenance records and an FMEA database, etc. In particular, linking to the HUMS data warehouse would provide valuable information for FADES. All of these aspects would require varying degrees of software development to bridge FADES with the various data sources. Finally, FADES is really a prototype, and customisation of the software tool should be expected – for example, adding component hierarchies, extending the type of information that describes components according to industry standards such as ATA for the aerospace industry.

The FADES Model uses as many building blocks as possible to build up the overall model. The basic building block concept for which the information hierarchy is developed is a component. For each component, a number of failure modes are identified. These failure modes are quantified using probabilistic descriptions such as degradation mechanisms which are defined in some domain or ageing variable, affected by environmental and operational factors and mitigated by maintenance actions. All these concepts are then combined to create a FADES model. The FADES model is thus a collection of all the concepts described above and consists of one or more components. To quantify the likelihood of failure in the context of a particular failure mode, the concept of degradation mechanism is used. Each failure mode has associated with it one or more degradation mechanisms which define the probability of that failure mode occurring. A mixture of Weibull distributions to determine the probability of failure of a component due to a particular failure mode is then used. Degradation mechanisms can be influenced by one or more factors which affect, encourage, or in less common cases, inhibit the degradation process. For example, dusty conditions can shorten engine lifespan and sudden braking can lead to more rapid tread wear for car tyres. In the approach used, two distinct types, environmental and operational factors are considered. Degradation mechanisms are measured in terms of ageing variables. The most intuitive ageing variable is time – this might be real time passed since the manufacture or introduction to service of the component, or cumulative operational running time of the component. One of the key ideas behind FADES is to identify which ageing variables are relevant to a particular system and to quantify probabilities of component failure within that system in terms of multiple ageing variables. Some of the ageing variables can be based on time, for example operational time for an engine, vehicle driving time, etc., while others can be measured in terms of some specific events, number of engine starts, number of experienced take-offs and/or landings, etc.

Since the tool is intended to model maintenance regimes, it needs to capture the effects of maintenance actions. It is assumed that the state of a component can be restored to its fully functional state by performing a maintenance action. This is a simplification that is made in the current version of the tool, as in general some maintenance actions can lead to partial improvements of the state of a component, while some only prevent or slowdown of further health degradation. Maintenance actions are linked to failure modes rather than directly to the component. There may be multiple maintenance actions for the same failure mode which, for example, can differ with respect to cost and effectiveness. FADES is intended to capitalise on the development of monitoring technologies such as HUMS. Therefore information about available measurements (observations) related to different aspects of the maintenance can be included in the FADES as observations. In the most typical scenario, observations are HUMS data streams – accelerator readings, temperature measurements, etc. It is likely, however, that derived channels can be of more use. The derived channels are transformed or interpreted original HUMS measurements: for example, accelerometer readings may be interpreted as touch-down of the aircraft. One or more observations can be associated with either a degradation mechanism or a factor. For each association two numerical values related to the reliability of the observation are assessed: sensitivity (how likely the observation is to be present given the degradation mechanism or factor is present) and specificity (how likely is the observation to be present given the degradation mechanism or factor is not present).

The FADES model allows for sharing the same concept entities (for example, an ageing variable of Engine Running Time) among different parent entities. In this way the FADES model is defined as sets of different entity types (components, failure modes, etc.) and dependencies between these entities (subject to some constraints) which form a graph, rather than a tree. This approach allows, for example, dynamic Bayesian network models to be built in different temporal domains determined by ageing variables and for them to be considered independently of each other. The results obtained from these models are then combined in order to provide predictions for the likelihood of failure given a particular usage pattern – for example, high mileage, relatively small number of engine power-ups (long trips), no high engine rpm. This approach allows a comprehensive, multi-dimensional model of likelihood of failure to be built, and the production of specific predictions for individual vehicles in the fleet.

FADES is implemented as stand-alone software that can be installed on a computer or a laptop. FADES was implemented using the Java programming language which makes FADES platform independent – the only requirement to run FADES is to have Java Virtual Machine installed on the computer system. The FADES tool in its current form is an initial framework that lays the foundations for specialised implementations. It was developed with the intention of being generic and easily customisable. One example of customisation is the first Case Study described below. Table 1 below summarises the generic aspects of the

FADES tool and those aspects that should be customised in order to deliver the full value of the proposed approach.

Table 1. FADES Attributes that need to be customised.

GENERIC	*CUSTOMISED*
Software tool	Specialised software modules within the generic framework
Concept Hierarchy (components, failure modes, degradation mechanisms, etc.)	Properties of the entities in the Concept Hierarchy (e.g. Part numbers)
Data storage format	Categorisation of entities to allow for industry standards (e.g. ATA Chapters)
	Underlying data base

One particular aspect of customisation is of particular importance – the use of a database with FADES. Even though this functionality was implemented, it is envisaged that the database schema should be re-implemented to fit the organisational context for a specific FADES application. Therefore, the current database definition that is developed with the FADES prototype should be regarded as a technology test-bed rather than a completed solution. The FADES software in its current form is in fact a prototype. It is intended to be customised and its reliability should be thoroughly tested before fielding it. In fact any application of FADES should be done in close collaboration with the authors of the tool to fully utilise its capabilities.

Predictive Maintenance Probabilistic Decision Support (PMPDS) Tool

The Predictive Maintenance Probabilistic Support (PMPDS) tool is designed to improve maintenance effectiveness and service provision by providing a decision support tool that delivers intelligent analysis of a platform's past and future usage data in order to predict likelihood of failure of selected components and sub-systems. The tool is capable of combining engineering and maintenance personnel's tacit knowledge with the data collected by Health and Usage Monitoring Systems (HUMS). The tool is primarily intended to enhance the capabilities of intelligent usage data collection on modern complex engineering systems.

Setting the period between maintenance activities based on elapsed time or hours of use alone is inefficient. Prognostic systems, which predict when specific failures are most likely to happen, based on the current state of the system, its usage history and planned future usage offer the opportunity for optimising maintenance actions and consequently reducing cost without compromising safety and availability. In the early years of HUMS development, it was believed, somewhat naïvely, that collection of sensor data would be sufficient to implement predictive maintenance. Unfortunately, the reality showed that there are fundamental problems with the data collected by HUMS:

- the amount of data generated by the sensors is far beyond our capabilities of drawing conclusions without automated analysis,
- the data does not cover all aspects required to implement predictive maintenance (for example, repair records), and
- the data needs additional, often very sophisticated, analysis to turn it into actionable information.

Another factor is the lack of understanding of the physics of failure; in many situations it is not clear which measurements are most relevant to the estimation of the residual life in the system and so many of these measurements might simply not be collected. Furthermore, not all information relevant to failure prediction is available in the form of digital records. Typical examples of information which is not available include: failure modes of the equipment, repair action records, and intended future usage patterns of the equipment. Some of these aspects, however, could be obtained from engineering and maintenance experts.

Prognostic systems are particularly challenging to implement for military systems, as these systems are used in a wide range of different environments and with greatly varying intensity to cope with operational demands; but at the same time predictive maintenance can offer great benefits. To model usage patterns and failures arising from them properly, it is necessary to combine all available forms of data, including expert knowledge. The approach taken by the PMPMDS tool is to combine the data within a probabilistic graphical framework known as a Dynamic Bayesian Network (DBN). However, the models are difficult to create, requiring skilled individuals with expertise in both modelling methods and the application area. This tool is therefore intended to semi-automate the model creation process in order to reduce costs related to the development of models for predictive maintenance. The benefits that are projected from the use of the tool include, but are not limited to:

- Provision of support for analysis of current vehicle health based on wider knowledge than only HUMS data.
- Reduction of the cost of developing prognostic models combining expert knowledge, system usage and health data.

The PMPDS tool is closely related to the FADES tool and uses the data it collects to automatically create the back-bone of the prognostic models. Even though the PMPDS tool can be used independently, the best value is likely to be achieved if PMPDS is used with FADES, in particular, with the formalised maintenance and failure patterns knowledge which FADES can input to PMPDS. PMPDS is designed to automatically extract the information necessary to produce prognostic models using a BN modelling approach from the data structures of the FADES tool.

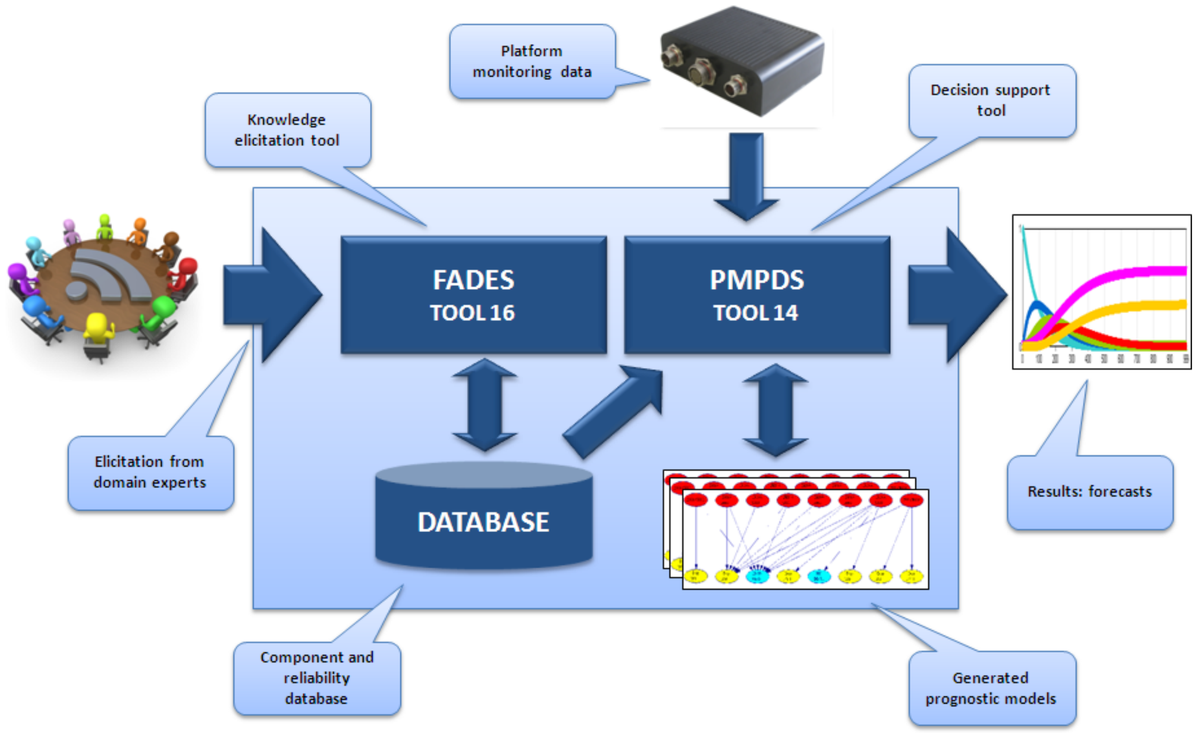

Figure 2. FADES & PMPDS Tool Combined Solution for Predictive Maintenance

Figure 1 shows a representation of the combined use of FADES and PMPDS. The key idea behind the solution is to combine multiple sources of information and data to implement prognostic models for predictive maintenance; it will therefore exploit hard evidential data produced by automated monitoring systems together with tacit knowledge existing within the organisations responsible for delivering service and among the users. The types of information elicited by FADES as described above, include identification of components that are suitable for predictive maintenance, and their associated failure modes, failure frequencies and patterns, factors that influence these failure patterns, maintenance actions that rectify them, and possible links to available HUMS data. All this information is formalised, structured, and recorded. Some of this information is used by PMPDS to enable automated Bayesian network model construction that fuses the tacit knowledge formalised with the help of FADES with the system-specific HUMS data streams to create numerical models for failure prediction. The models created by PMPDS are then able to provide estimates of likelihood of a component failure based on HUMS data collected for a specific vehicle – based on its unique usage history. These estimates allow informed decisions to be made regarding the maintenance actions that are specifically based on a unique context for each platform, delivering a solution enabling true condition based maintenance (CBM).

In order to take full advantage of the tool, an organisation should be prepared to commit some effort to adapt and customise the PMPDS tool to its specific requirements and service needs. Figure 2 presents the structure of the tool showing which aspects are provided as ready off-the-self products, and which aspects will need to be customised to a particular application. The PMPDS tool offers a formalised and semi-automated modelling technique for estimating likelihood of failure of selected components within the system under study. The conversion process that takes the FADES data structures and turns it into a DBN model is implemented as software and is a part of the PMPDS tool.

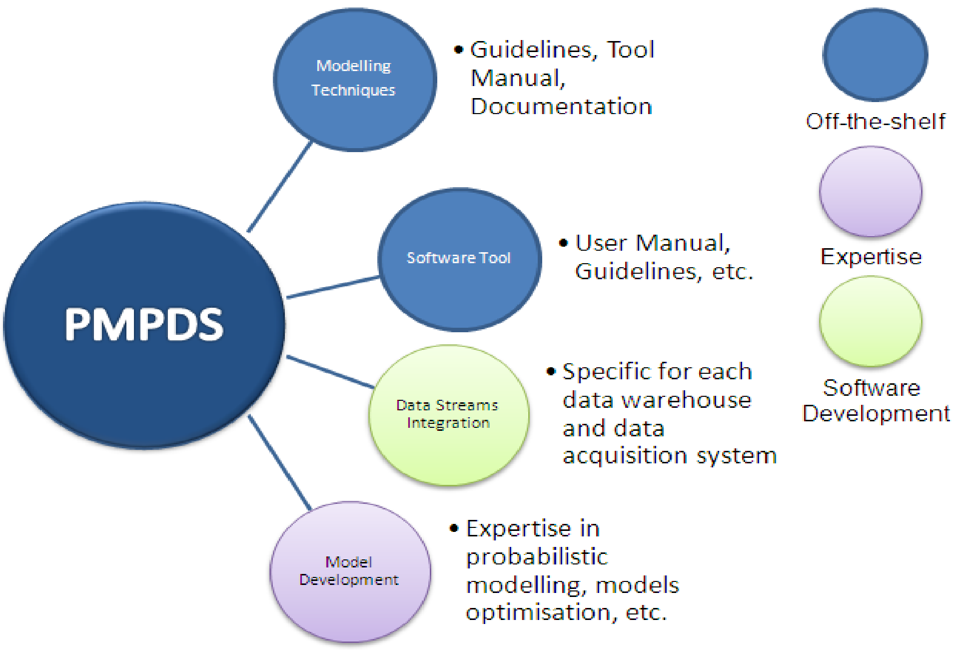

Figure 3. PMPDS Tool Structure

To exploit the PMPDS as a practical tool, it is necessary therefore to integrate the organisation's data infrastructure for HUMS with the models developed using the PMPDS tool. This task should not be underestimated. Substantial software development effort is likely to be required as PMPDS generates models, but does not provide software infrastructure to link the models with the HUMS data feeds; these are always specific to the application and always have to be hand-crafted using experts' domain knowledge. Even though PMPDS offers semi-automated DBN model creation, in reality models generated automatically are not always suitable for immediate use and require some tuning or revision by a knowledge engineer familiar with the BN modelling technique. It should be made clear therefore that the PMPDS tool is intended to semi-automate the model creation process, but human intervention is still needed to prepare and validate the models before they can be used in practice.

Case Study

In the final stages of the tool preparation it was important to establish user support and feedback with the tools and various case studies were conducted under a Mini Knowledge Transfer Partnership (Mini-KTP) scheme. The aim was to establish knowledge transfer of the research and tool development from the University to an industry partner and to receive feedback about the tool's applicability in that environment. Two case such studies were conducted and are described below. In addition for the HUMS Cost Benefit tool, a voucher scheme was implemented by the KT-Box management in order to facilitate additional application of the tool in practical situations. The voucher provided additional funding to allow a consultant to go to a user and provide some initial training in use of the tool, carry out an application of the tool and provide feedback to the development team. Three applications were conducted providing excellent feedback for further refinement of the tool.

Case Study

Cranfield University and Dytecna Limited co-operated under Mini-KTP to develop and demonstrate the integration of the Dytecna HUMS Vehicle Monitoring Unit (VMU) box with the prototype of Cranfield University's software tools for knowledge elicitation for the purpose of prognostic modelling. The project was small in scope and involved only 20 days of effort from the two partners, but as such it served as a proof of concept for developing a prototype of a solution aimed at bridging software developed at Dytecna and Cranfield University. The project also served as a platform for exploring the commercial value of integration of the two capabilities.

The Dytecna VMU is a configurable Health and Usage Monitoring System that is being installed on different third party vehicles. The VMU is capable of capturing multiple channels from various types of inputs, interpreting and recording them. Consequently the VMU needs be highly configurable and this is achieved by means of special configuration files that control the channels recorded by the VMU. These configuration files, among other aspects, specify which signals are to be processed, interpreted and recorded.

The Cranfield University FADES software tool for knowledge elicitation is designed to enable prognostic modelling and was thus the core part of the project. The knowledge of degradation and failure models elicited using the FADES tool and supported by actual data produced by HUMS, such as Dytecna's VMU, can provide the basis for reliable prognostic solutions. The Dytecna's VMU is a necessary tool to provide HUMS data that would be used by prognostic models derived from the data collected by FADES. On the other hand, FADES can serve as a tool to specify which measurements (channels) are required by a customer to provide prognostic capabilities. In order to exploit the potential of the two solutions, a bridge between the two needed to be developed in a form of a tool that would allow identification of the channels recorded by the VMU that are most relevant for the prognostic purposes (for example, some of the channels may be useful for diagnosis, but not prognostics). At the same time, the VMU data recording capabilities may require some extensions in order to fully exploit data features for prognostic modelling. That led to the development of a new format for configuring the next generation VMUs that would potentially allow integration with FADES tool.

The developed tool is intended to bridge the Dytecna's VMU data formats (both existing and newly defined) for VMU configuration with the data structures for the FADES model which encodes the prognostic concept hierarchy developed at Cranfield University. The basic data interdependencies for the software developed for this project are shown in Fig. 1.

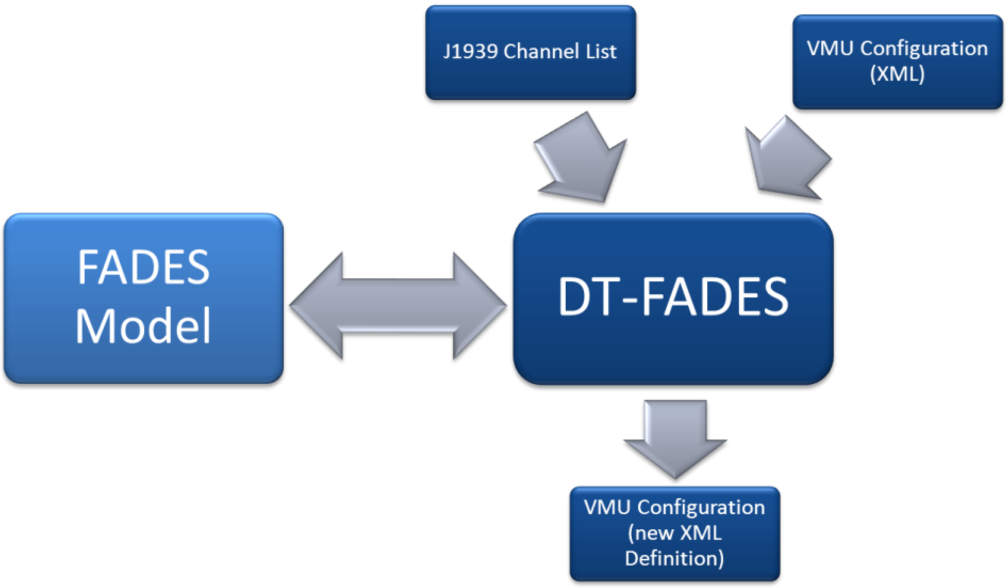

Figure 4. The basic data interdependencies for the software developed for this project

One of the key challenges related to the exploitation of HUMS in general is the identification of subsets of the captured data that represents actual value for the business operations. The modern engineering platforms equipped with the state of the art HUMS are capable of producing large volumes of data streams and these streams are used for different purposes (e.g. engine control, providing information for operator, strictly usage monitoring) and some of them are collected with the assumption that they potentially can be useful in the future. There exists disparity between the ease with which the HUMS produce data and the on-board data storage capabilities. The main reason for this is that the cost of data storage is relatively higher than the cost of data generation. Practical solutions to this problem include data-reduction techniques (sacrificing details of the data in favour of data summaries that require much less storage capacity) or selective recording of the available channels. The Dytecna's VMU allows for both, but in particular the selective recording of the data is of the interest of this project.

It should be expected that only some of the data streams can provide potentially useful information required to deliver prognostic capabilities. The practical challenge is to identify those data streams. The FADES tool can offer an approach to this problem that is based on the premise that the designers, users, and the maintenance personnel are able to identify relevant HUMS measurements for the degradation mechanisms during the elicitation process facilitated with use of FADES and subsequently that all these are stored in a FADES model. Therefore the FADES model can be used to provide a list of measurements (channels) that are suggested by the user. In a broader sense, FADES can be used as a tool to facilitate a communication between that Customer's technical requirements and the set-up of the Dytecna's HUMS.

CONCLUSIONS

Even though the KT-Box was a three year project, not all this time was spent on developing tools. The first twelve months were committed to turning the research into tools – in this process intensive collaboration between academics and industry representatives, who played a role of friendly critics, was the key to success. Resolving legal issues related to sharing intellectual property rights and details of non-disclosure agreements between multiple industrial and academic partners further delayed the actual start dates for development of the tools. Consequently, there was great intensity of work toward the end of the three years. Some of the work continues even though funding has ceased, as it was deemed to be promising and of genuine interest to industry partners. For instance further development and application of the FADES and PMPDS tools is now underway using a gas turbine engine and a dozen or so subsidiary 'components' or sub-systems in order to demonstrate the effectiveness of the tools. It is nevertheless clear that moving academic research into practical outputs that are of use and are effective in real life applications is a challenge in general, but one that must be overcome if economies are to grow and survive. The mini-KTPs and practical demonstrations, albeit in limited length case studies, particularly showed the benefit of this approach and have delivered some very useful results that have every prospect of fostering further applications.

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