likely those failures are. This information can be used to verify that decomposed safety requirements are being met and, if performed iteratively, can also inform the direction of the design by highlighting potential weakpoints in the system.

All analysis and optimisation processes in HiP-HOPS are performed on an architectural system model which identifies material, energy, and data transactions among components (Fig. 3).

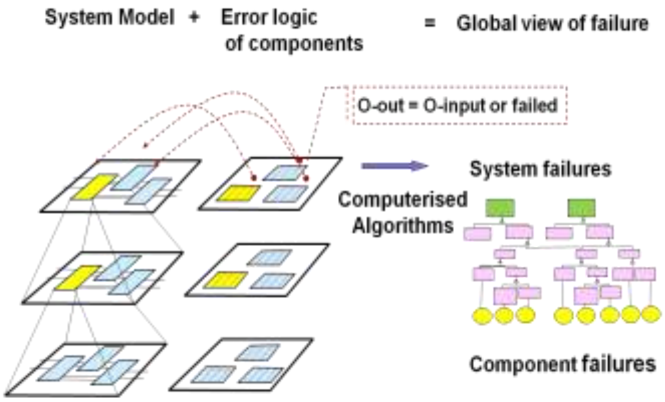

Fig. 3. Modelling and Dependability Analysis in HiP-HOPS.

The model can be hierarchical if necessary to manage complexity. In the case of a hierarchical model, subsystems enclose architectures of more basic subsystems and components.

The dependability analysis process in HiP-HOPS then proceeds in three phases. The first phase is the *annotation phase*: each component in the model is annotated with its local error logic, describing the errors that can occur in the component and how it responds to deviations of its inputs. HiP-HOPS defines a language for the description of this error logic. In the basic version of this language, the error logic of a component can be specified as a list of internal failure modes of the component and a list of errors or deviations as they can be observed at component outputs. Each component failure mode is optionally accompanied by quantitative data, for example a failure and a repair rate. Output errors carry Boolean expressions which describe their causes as a logical combination of component faults and similar errors observed at component inputs. For example, to describe an omission of output from a component caused by either an omission of corresponding input or an internal failure mode, we can say:

```
omission-component.outputPort =
     internalFailure OR
     omission-component.inputPort
```

Here `internalFailure` is a failure mode of that component and may have probabilistic failure data attached, e.g. a failure rate in terms of failures per hour. `omission-component.inputPort` represents an error or deviation at the component's input port of type "omission", i.e., a lack of input. The logical OR operator indicates that the output deviation — omission of output — is caused by either the internal failure mode or the lack of input to the component.

Input and output errors referenced in the error logic are described qualitatively and typically represent different classes of failures, such as the omission or commission of parameters or qualitative deviations from correct value (i.e. hi/low) and expected timing behaviour (i.e. early/late). These are not fixed and analysts may use whatever nomenclature they wish as long as the usage is consistent across the model.

Collectively, a set of failure expressions that logically explain all possible errors at all output ports of a component provides a model of the error logic of the component under examination. This model can be stored in a library. For simple components, e.g. sensors and actuators, such models could be re-used across different applications to simplify the manual part of the analysis and the overall application of the proposed technique.

The second phase of the HiP-HOPS dependability analysis process is the *synthesis phase*. Using the error logic associated with components, computerised algorithms automatically determine how errors propagate through connections in the model to cause functional failures at system outputs. These are the failures that analysts are typically interested in identifying and analysing. For example, in a car, such functional failures may include the loss of steering or braking. Since HiP-HOPS shows how individual failure modes in components can combine and lead to functional failures at system outputs, a system failure such as loss of braking may be seen to be the result of an actuator failure.

This global view is captured in a set of interconnected fault trees. These fault trees show how the leaf nodes of the trees — representing the component failure modes and their local effects — can logically combine and propagate though the system to cause the top events of the fault trees, which represent the functional failures of the system (Veseley *et al.*, 2002). The interconnections between the trees represent dependencies in model, e.g. the failure of a common power supply or a global condition that may affect more than one system function. Common cause failures, such as flooding of physically co-located components, can also be represented in HiP-HOPS.

Once this is done, the third phase of HiP-HOPS is to perform analyses of this global system error model: the *analysis phase*. First, an automated fault tree analysis is performed for each of the functional failures in the system. HiP-HOPS can perform both qualitative and quantitative analysis of fault trees. Qualitative analysis is used to establish the minimal cut sets of the fault trees — the smallest combinations of failure events necessary to cause system failure — which more readily indicate how system failures may occur. Quantitative analysis is also possible when probabilistic parameters have been provided at component level and is used to predict the reliability and availability of the system.

In the final stage of the analysis, the complex body of logic encoded in the set of interconnected fault trees is simplified by an automated algorithm which translates it into a simple table of direct relationships between component and system failures. In a similar way to a classical FMEA, this table determines, for each component in the system and for each failure mode of that component, the effect of that failure mode on the system. The table shows which system failures (if any) each failure mode causes, both by itself and in conjunction with other events.

Note that in a classical manual FMEA only the effects of single failures are typically assessed. Thus, one advantage of generating an FMEA from fault trees is that fault trees record the effects of combinations of component failures and this useful information can also be transferred into the FMEA. The FMEA shows all the functional effects to which a particular component failure mode contributes, both individually and as part of a combination. This is particularly useful as a failure mode that contributes to multiple system failures is potentially more significant than those that only cause a single top event. Consequently, this type of FMEA can also help analysts to determine the level of fault tolerance in the system, i.e., to determine whether the system can tolerate any single failure or any combination of two, three or more component failures.

It is clear that both quantitative and qualitative analyses in HiP-HOPS can play a dual role: either to help verify requirements or stimulate useful design iterations by highlighting weak areas of the design.

We should note that experimental versions of the tool enable use of an extended language where it is also possible to express a wider range of failure semantics. For example, wildcards can also be used to describe more abstract patterns of relationships between output and input deviations. This allows statements such as "there will be an omission of all outputs in response to any input error" (Wolforth *et al.*, 2010), which assists in the reuse of error logic descriptions across components with different interfaces but similar failure behaviour.

More significantly, recent work has extended the range of systems that can be effectively analysed by HiP-HOPS. Because it is based on classical Boolean fault tree analysis algorithms, traditionally HiP-HOPS was limited to analysing only those systems that could be represented with Boolean failure behaviour. However, many safety-critical systems exhibit more complex behaviour: they may be dynamic, rely on sparse or uncertain probabilistic data, or express non-coherency in their failure logic.

Experimental versions of HiP-HOPS provide support for all of these types of scenarios, as will be explained next.

3.3.1 Dependability Analysis of Non-Coherent Systems

Some safety critical systems exhibit non-coherent failure behaviour, which means that certain system failures can only occur if another event has *not* occurred. This other event may be an ordinary system event or it could be another failure event. Such scenarios may occur in multitask or multi-phase systems where the causes of system failures can only be identified once the system successes have been taken into account (Andrews, 2000). For example, a failure in task A may only occur if another task B has succeeded: failure of task B therefore prohibits failure of task A. In fault trees, this condition is typically represented using a NOT gate. HiP-HOPS has been extended with the capability to model and analyse this type of scenario (Sharvia & Papadopoulos, 2008). HiP-HOPS failure expressions can include NOT gate conditions so that the effects of failures not occurring can also be taken into account during system analysis. This involves the generation of the prime implicants, i.e., the effects of different failure states of multiple components in combination, at the expense of a slight performance overhead. The resultant fault trees and FMEA tables then show that some system failures may only occur if certain system conditions or events do *not* occur.

3.3.2 Dependability Analysis of Dynamic Systems

In a dynamic system, the system behaviour changes over time. This could be because there are multiple phases of operation, e.g. as in an aircraft with distinct take-off, flight, and landing phases, or it could be because the system behaviour changes in response to different events (whether normal system events or failure events). Safety-critical systems are increasingly dynamic in nature as they frequently include the capacity for partial self-repair in response to failure, e.g. through the use of backup components, fallback to degraded modes of operation, or automatic detection and correction of certain types of errors.

Classical safety analysis techniques such as FTA and FMEA struggle to model these types of scenario. The key shortcoming is the inability to distinguish between the effects of different *sequences* of events, not just combinations of events.

Consider the triple redundant system of Fig.4:

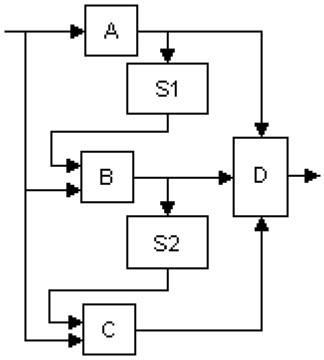

Fig. 4. Dynamic system with two backup components.

System functionality is initially provided through component 'A', which is the primary component. The monitor 'S1' observes component A for any deviation of its outputs. If detected, the sensor activates component 'B', the first backup component, and moves to a degraded mode of operation. Similarly, once component B has been activated, monitor 'S2' begins monitoring B for output deviations and, if any are detected, activates the final backup component 'C'. Component 'D' represents the system output.

A standard FTA of this system might indicate the following causes of system failure:

1. Omission of input to the system
2. Failure of A *and* Failure of S1 to detect failure of A

3. Failure of A *and* Failure of B *and* Failure of S2 to detect failure of B
4. Failure of A *and* Failure of B *and* Failure of C

At first glance, these causes would seem to make sense. However, they do not take into account the sequence of events. For example, consider the second cut set: if component A failed first, allowing S1 to activate component B, a subsequent failure of S1 would have no further effect on the system — it is already running in its degraded mode using backup component B. Therefore this cut set is pessimistic, as only one sequence (failure of S1 *before* failure of A) will lead to system failure. Similarly, a failure of component B before component A means that B will never be activated by S1, and thus monitor S2 will never be able to activate the final backup component C. In this case, the last cut set is optimistic, because some sequences of events will result in system failure even without the failure of C.

To remedy this general problem, a range of temporal and dynamic extensions to fault trees have been proposed, such as the Dynamic Fault Tree approach (Dugan *et al.*, 1992; Veseley *et al.*, 2002). For HiP-HOPS, we have developed an extension to the fault tree analysis known as Pandora (Walker *et al.*, 2007). The Pandora technique is included as part of HiP-HOPS and adds new temporal logic gates to enable fault trees to model sequences of events and thus better capture the failure behaviour of dynamic systems.

In particular, Pandora adds three new gates:

Priority AND gate (PAND): `X < Y`

Simultaneous AND gate (SAND): `X & Y`

Priority OR gate (POR): `X | Y`

The PAND gate represents a sequence: event X must occur before event Y, but both must occur. The SAND gate represents simultaneous occurrence. The POR gate represents a condition: event X must occur before event Y if event Y occurs at all.

By defining a set of new temporal laws that apply to these gates, analogous to the laws of Boolean logic, Pandora makes it possible to perform a qualitative analysis of temporal fault trees and obtain the minimal cut sequences — the smallest sequences of events necessary to cause the system failure.

Using Pandora, the minimal cut sequences of the example triple redundant system would be as follows:

1. Omission of input to the system
2. Failure of S1 *before* Failure of A
3. Dormant failure of B *before* Failure of A
4. Failure of S2 *before* Failure of B *or* A
5. Failure of A *before* Failure of B *and* Failure of C

These cut sequences better capture the dynamic behaviour of the system. The failure of a monitor after the failure of the monitored component is no longer modelled as a system failure and the scenario where B can fail dormant before A is properly represented.

In the absence of quantitative data, Pandora can provide useful insight into system failure. Where quantitative component failure data is available, quantitative analysis of Pandora fault trees is possible. The analytical approach (Edifor *et al.*, 2012, 2013) uses mathematical expressions to probabilistically evaluate the Pandora temporal fault tree gates based on exponentially distributed failure data. Using this approach, analysts can determine the overall reliability of a system. They can also identify the critical parts of the system by determining the relative contributions of the various system components to the causes of system failure. Once the critical parts are identified, reliability may be improved by e.g. including redundant components or using components with lower failure rates.

Petri Nets (PNs) have also been used to develop an approach for probabilistic evaluation of Pandora fault trees based on exponentially distributed data (Kabir *et al.*, 2015). In this approach, the fault trees are quantified by translating them into Generalised Stochastic Petri Nets (Marsan *et al.*, 1996). Similar to the analytical solution, this approach can evaluate system reliability and criticality of components. In addition, it can also verify the correctness of the qualitative analysis. To allow the analysts to perform quantitative analysis of Pandora fault trees with any kind of distributions of data, Kabir *et al.* (2014a) have developed a methodology based on Bayesian Networks. Although others have developed approaches to convert Boolean fault trees to Bayesian Networks (Bobbio *et al.*, 2001), this approach instead transforms Pandora temporal fault trees to evaluate system reliability and criticality of system components. In addition to the predictive analysis, this approach allows the analysts to perform post-hoc diagnostic analysis, a process which involves calculating and updating the posterior probability of basic events given observed evidence of the system failure.

3.3.3 Dependability Analysis in Conditions of Uncertainty

As already mentioned, HiP-HOPS can perform quantitative analysis to predict the reliability and availability of systems if the probabilistic parameters of system components (e.g. failure rate or failure probability) can be provided. However, this means that the quantitative analysis is entirely dependent on the availability of this quantitative failure data. For many complex systems, it is often difficult to obtain precise failure data of components from past occurrences due to lack of knowledge about the systems, scarcity of statistical data, and changes in operating environment of the systems (Tanaka *et al.*,1983; Singer, 1990). This situation is particularly relevant in the early design phases when system analysts consider new or undetermined components for which there is no quantitative data. In such situations, expert human judgement in linguistic terms, e.g. ‘very low, low, high’ may be used to determine uncertain failure data of components.

Fuzzy Logic is a branch of mathematics which has the capability to deal with linguistic variables and it provides efficient way to draw conclusions from imprecise data. A variety of approaches (e.g. Suresh et al. (1996); Yang (2012)) have been proposed based on fuzzy set theory to allow classical and dynamic fault tree analysis with uncertain data. Recently, a fuzzy set theory based methodology has been proposed by Kabir *et al.* (2014b) to quantify Pandora fault trees with uncertain data. In this method, fuzzy operators for the new fault tree gates have been developed and fuzzy data have been used in the quantitative analysis instead of fixed data. As a result, the system unreliability is obtained as fuzzy numbers. This methodology can also determine the criticality of system components based on their relative contributions to the occurrence of the system failure. By more explicitly highlighting the areas of uncertainty in the failure data, this method can lead to a more effective quantification of uncertainty in dynamic systems. It is important to highlight that the results of quantitative analysis can only be as reliable as the input data, and the inclusion of fuzzy data cannot improve the accuracy of the results. However, techniques such as importance measures allow analysts to see the relative contribution of different system elements to the overall failure probability. This helps to overcome the limitations of uncertain quantitative analysis results by focusing on the relative values rather than exact values, identifying the areas of the system design most sensitive to improvement.

3.4 Architecture and Maintenance Optimisation

Let us assume now that a team of analysts is designing a system, that we have decomposed the dependability requirements across the architecture, and that an analysis from a MBSA tool suggests that the system does not meet all of those dependability requirements. At this stage we need to improve the design somehow so that it does meet the requirements, as shown by a second round of analysis. There is typically a range of options available to improve a design, including:

a) replacing a component with a more reliable and expensive component

b) replacing part of the architecture with a more dependable alternative

c) replicating components in fault tolerant schemes so that failures are tolerated

d) increasing the frequency of maintenance, an action that prolongs the useful life of components and thereby increases the reliability of the system.

The difficulty is that in a typical system design, there is a very large number of possibilities for substitution, replication and maintenance scheduling. For instance, in a system of n components, if there are two suppliers for each component then there are 2^n configurations which equates to $1.26e^{30}$ configurations when n=100. Each configuration will have its own dependability and cost performance. It is clear that in such situations analysts are confronted with a multi-objective optimisation problem, where the objectives may include dependability, cost, weight and other properties.

It would be prohibitively expensive to investigate more than a handful of these possible configurations manually. Therefore, to optimise such designs, we have developed an extension of HiP-HOPS that employs genetic algorithms to perform multi-objective optimisation of architectures with respect to dependability and other attributes (Papadopoulos and Grante, 2006; Papadopoulos *et al.*, 2011). This is a separate optimisation process to the allocation of dependability requirements; architectural optimisation takes place as a way of finding a design that meets the devolved dependability requirements, which may themselves have been set as a result of an allocation optimisation process.

The architectural optimisation concept is illustrated in Fig 5. As with dependability analysis in HiP-HOPS, the process starts from a model of the system. However, this time the model is not fixed — it has *variability*, i.e., components can have multiple alternative implementations. These points of variability may involve different parameters of components or may involve architectural changes, e.g. replacing a single component with a more fault-tolerant design using primary and backup components. For example, a sensor can be chosen from two different suppliers, with each choice having its own cost, weight, performance, and failure characteristics. Subsystems can also carry alternatives, e.g. a subsystem can have two different implementations that provide the functions using different sets of components and different architectures. There can be options for replication of components with known patterns of fault tolerance, e.g. a primary-standby configuration, or multiple parallel channels with majority voting. Finally, there can be options for the scheduling of component maintenance.

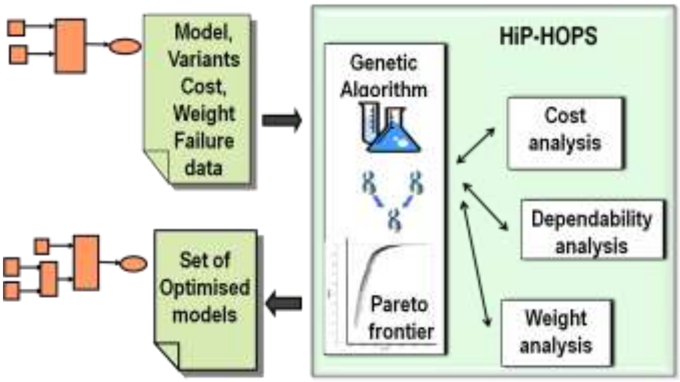

Fig. 5. Architecture optimisation in HiP-HOPS.

Once the system model has been annotated to include these variable possibilities and any further required information, including associated cost and failure data etc, the model is given to HiP-HOPS, which then applies an evolutionary optimisation process. In the context of this process, HiP-HOPS creates a population of candidate designs by resolving the variability of the model, i.e., fixing variation points in the model by selecting particular design options. Each candidate design is then evaluated with respect to the objectives of the optimisation. The evaluation is performed using the analysis algorithms of HiP-HOPS. The reliability and availability of a candidate design are automatically calculated from the generated fault trees. A quantitative measure of safety is established from the FMEA, using, for instance, the number of single points of failure that contribute to severe system failures. HiP-HOPS also includes simple summative cost and weight functions. External plugins can also be designed to enable more precise evaluation of cost, weight or other objective functions. For example, experiments with timing and schedulability have been reported in (Walker *et al.*, 2013).

Once candidate designs have been evaluated, they are ranked according to their performance and a Pareto frontier is formed showing the best designs in the current population. Roulette wheel selection, a random process biased towards the better performing designs, is used to select candidates to form the parents of the next generation. Through application of classic genetic operators such as mutation and crossover, a new population is then formed and the process of evaluation and ranking is iterated. The result of this process over a number of successive generations is a gradual improvement of the average performance of the population that is evident in the progressive improvement of the Pareto frontier. The process is terminated on meeting certain constraints or after a specified number of generations. The result is a set of models that give optimal or near optimal trade-offs among the objectives of the optimisation.

Via this process, designers can take informed decisions about the selection of components, subsystems, the location and type of replication, and about maintenance scheduling, all the while making sure that dependability requirements can be met whilst minimising costs.

As an example of this architectural optimisation process, HiP-HOPS was applied to a high-level abstract design of a vehicle pre-collision system and an evolutionary optimisation technique was used to achieve balanced solutions with respect to dependability and cost (Adachi *et al*., 2011).

The pre-collision system is an automotive safety technology that avoids or reduces the damage caused by a collision. The system supports drivers by issuing warnings when a potential collision threat is identified and activates emergency braking if the driver fails to apply the brakes. To improve system fault tolerance, a number of fault tolerance mechanisms were considered. These mechanisms may be applied to various locations in the system architecture to achieve greater dependability, albeit at an increased cost. The mechanisms include *self-protection, self-checking, checkpoint-restart and process-pair. Self-protection* and *self-checking* are functions which can be used for error detection. In *self-protection*, the component protects itself from external disturbances by detecting errors propagated from other components. In *self-checking,* a component detects internal errors and prevent the propagation of those errors to other components. *Checkpoint-restart* not only detects failures, but also recovers from errors by restarting the component. Finally, *process-pair* is a fault tolerance technique which uses redundancy realised by two identical software components. These are typical mechanisms for detection and correction of errors which give a sophisticated range of options to consider in early design. To model situations where these fault tolerant components miss some failures which need to be detected, an additional event *miss* was included in the analysis. Fault tolerant mechanisms may also experience failure, so the event *failure* is used to represent internal malfunction for the fault tolerant components. Information on failure expression and failure rate were included for each of the components in the system with reasonable assumptions about plausible hardware and software failures. The HiP-HOPS optimisation algorithm was finally employed to select the optimal location and types of fault-tolerance mechanisms in an improved version of the system. From a total design space of about $12^7 \approx 3.6\times10^7$, in just 5 minutes it was able to find 8 Pareto optimal solutions that provided a good trade-off between risk and cost while meeting the required constraints (see Adachi *et al* (2011) for further information).

The case study showed that insight into the optimal use of fault tolerance can be arrived at much more rapidly with the aid of automated tool support. The vast number of different options, let alone the time required to evaluate and compare these options, would make an equivalent manual process infeasible. Thus metaheuristic approaches allow a designer to obtain significant improvements in reliability and cost performance.

3.5 Model transformations from Architecture Description Languages

HiP-HOPS has also been used to support the development and analysis of systems modelled using Architecture Description Languages (ADLs), particularly the Architecture Analysis & Design Language (AADL) (www.aadl.info) and the automotive EAST-ADL (www.east-adl.info).

EAST-ADL provides an integrated and systematic support for the modelling of automotive systems. The growing adoption of model-based engineering techniques like EAST-ADL is driven by the need to better-manage advances in functionality and corresponding increases in the complexity of modern safety-critical embedded systems. The specification of EAST-ADL includes an error model which describes potential failures of design elements.

To enable advanced analysis capabilities like FTA, FMEA, optimisation and safety requirement allocations, the EAST-ADL error model is extended with HiP-HOPS semantics. This integration requires translation of models in the automotive domain to models in the safety analysis domain, i.e., a transformation of an EAST-ADL error model to a corresponding HiP-HOPS model. The concrete source and destination models are both represented in XML-based formats, which are EAXML and HiP-HOPS XML respectively. The translator tool is described in (Sharvia *et al.*, 2014). It involves conceptual semantic mapping between the domains and the representation of concrete models.

The benefits of ADL's such as EAST-ADL and AADL depend crucially on the availability of tools. Model transformation has been used make the optimisation capabilities of HiP-HOPS available to AADL models (Mian *et al.*, 2014). At the highest level of abstraction, the transformation consists of two parts. One part is concerned with the component specific error behaviour and the other part is concerned with the inter-component error propagation.

AADL uses an Error Model Annex for modelling component failure behaviour. Error models in AADL are state machines which specify how the state of a component changes in response to events or the states of other components. The model transformation incorporates a state machine to fault tree conversion algorithm described in Mahmud *et al*. (2012). This preserves the temporal properties captured in the state-machine.

The Atlas Transformation Language (ATL) (Jouault *et al*., 2008) is used to implement the transformation which has been developed as a plug-in for the AADL model development tool OSATE (https://wiki.sei.cmu.edu/aadl/index.php/Osate_2, accessed 2015).

4. TECHNICAL DISCUSSION

Key to all of the approaches presented in section 3 is the underlying system model in HiP-HOPS. At its core this is a architectural model that shows system elements and possible data, material, or energy flows between them. In the HiP-HOPS tool, this model can be exported from widely-used system modelling packages including Matlab Simulink (Mathworks, 2016), SimulationX (ITI, 2016), and various Eclipse-based UML modelling platforms such as Papyrus (Eclipse Foundation, 2016). As described in section 3.3, this model is further annotated with logical descriptions of the local failure behaviour of system elements. HiP-HOPS can then use this information to build a failure propagation network, describing how failures propagate through the system and revealing the dependencies between the different system elements. Because HiP-HOPS models are generated automatically from existing engineering models, it is easy to make modifications to the actual system model and then very quickly observe the effect this has on the analysis results.

Similarly, to support the different optimisation processes, HiP-HOPS requires information about the different possibilities. For decomposition of dependability requirements, it requires data on the system-level functional safety requirements, the cost heuristic to be used, and also what SIL algebra is to be used. For architectural optimisation, more detailed information is required in the form of different alternative implementations for each component to be used as a variability point, whether in the form of different parameters (e.g. cost, weight, reliability, maintenance schedules) or different sub-architectures (e.g. series, parallel, fault tolerance schemes).

Clearly, it is important for the model and its associated information to be correct. The failure propagation model is used to ensure independence between decomposed sub-elements of the system, without which the analysis results will be in error and the allocation of dependability requirements will be invalid. Consequently, we have made efforts towards improving the expressiveness of the HiP-HOPS model and its annotations, including modelling dynamic behaviour as explained in section 3.3.2 and for uncertain data as in 3.3.3.

However, due to the fact that analysis takes no more than a few seconds even for large systems with hundreds of components and many thousands of cut sets, it is relatively easy to identify errors, correct them in the model, and regenerate the analysis results compared to the effort that would be required to repeat a full manual safety analysis. The HiP-HOPS tool also performs a range of checks and reports various warnings and errors when it detects potential errors in the modelling or the failure annotations.

There are other limitations to our current work, typically consequences of being based on an easy-to-use Boolean logic rather than more complex state-based approaches. Logical loops in the failure propagation can be problematic (though are often symptomatic of modelling errors) and for this reason the tool works better at higher levels rather than on low-level electronic circuits. Repairable components are supported by the core safety analysis but not by all of the experimental extensions to the tool. Nevertheless, we are continually undertaking further work to try to address many of these limitations.

Ultimately any analysis is only as good as the data it is based on, and we rely upon the designers to provide accurate failure data for their system models.

5. RELEVANT WORK

There is very little work reported in linking MBSA to metaheuristics. In (Konak *et al.*, 2007) systems are represented as Reliability Block Diagrams (RBDs) which are subsequently optimised using meta-heuristics. HiP-HOPS enables optimisation of models which may have a networked architecture, i.e. they are not necessarily in parallel or series configurations as RBDs, and overcome the traditional assumption made in RBDs that a component or system either works or fails in a single failure mode. HiP-HOPS has been the first approach to direct optimisation of dependability on an architectural model. Other tools for architecture optimisation, with the possibility of adding arbitrary quality properties as objectives, include ArcheOpteryx (Aleti *et al.*, 2009) and PerOpteryx (Koziolek, 2011). The scope of these tools includes architecture optimisation but does not include the requirements allocation problem.

These tools require a reliability evaluation model such as a fault tree, RBD or Markov Chain for evaluating reliability. HIP-HOPS re-synthesises this model during the evolution of the system architecture by operating directly on an architectural model augmented with failure data. HiP-HOPS has also incorporated the first effort directed towards automatic allocation of dependability requirements (Papadopoulos *et al.*, 2010) and remains the only application of metaheuristics in this area.

Mader *et al.* (2012) proposed an approach for ASIL allocation where a linear programming optimisation problem is formulated to discover a solution that minimises the sum of ASILs as-signed across the system architecture. Zhang *et al.* (2010) proposed a workflow for embedded system development, which includes fault trees, FMEA and ASIL allocation based on a qualitative risk graph method. Dhouibi *et al.* (2014) introduced a method for ASIL allocation which is based on interpreting the allocation problem as a system of linear equations. Bieber *et al.* (2011) presented a theory to formalise the ARP4754-A DAL allocation rules and the DALculator tool to support automatic DAL allocation via integer programming optimisation. The starting point for these approaches are minimal cut sets of fault trees. Instead, HiP-HOPS starts from architectural models, offering the advantage of being able to assess explicit or implicit dependencies in the model and its environment that may cause common mode failures.

6. CONCLUSIONS

The technologies of model-based design, dependability analysis and the application of heuristics to the design of dependable systems, including software intensive systems, have advanced in recent years. However, we have not yet seen the emergence of a design paradigm that employs these techniques synergistically and systematically from the early stages of design to enable cost-effective, dependability-driven optimal design refinement.

In this paper, we have outlined four challenges that remain unaddressed and sketched a model-centric paradigm for the design of dependable systems that brings these technologies together to realise their potential benefits. These benefits include:

- controlling dependability from the early stages via optimal allocation of requirements;
- effective top-down distribution and then bottom-up composition of dependable designs in collaborative environments, distributed across complex value chains;
- automation in the assessment of design proposals and prediction of dependability;
- decision support on optimisation of architectures for component selection, fault tolerance and maintenance scheduling;
- reuse of repositories of models and analyses both during design refinement and across projects.

Tackling the wide range of requirements to obtain these benefits requires a model-based design paradigm that draws upon state-of-the-art developments and knowledge from multiple fields, building on classical and temporal logic, biology-inspired metaheuristic techniques and modern model-based engineering principles. In this paper, we have shown that such a paradigm is feasible by discussing its embryonic incarnation within the HiP-HOPS method and tool. HiP-HOPS is presently the only MBSA method that applies metaheuristics across the lifecycle including the very early stages, addressing both requirements and architecture. The transferability of this work in model-based design has been demonstrated in the context of architecture description languages such as EAST-ADL (Walker *et al.*, 2013) and AADL (Mian *et al.*, 2014).

We do not claim that we have addressed the enormous challenges discussed in section 2. Our modest aim was to show that this synthesis of bio-inspired techniques with logic has the potential to improve the field of MBSA by enabling useful functionalities that were previously unexplored. This is where we see the value of the paper and we hope that this modest claim has been substantiated. Our experiments, which are described in many of the references, show practical improvement in design using these functionalities. One can see Pareto fronts of generated solutions moving towards better and better tradeoffs. We have still not attempted a systematic quantification of these improvements. One way to achieve this is by tasking engineers with developing solutions to problems also solved with the aid of metaheuristics. One could then plot these solutions on Pareto fronts and could measure the distance in performance between manually derived and automatic solutions.

There are of course many other challenges that remain to be addressed as this work develops further within the field of model-based design and MBSA. These include the representativeness and completeness of models, the relation of models to code, the modelling and analysis of commercial off-the-shelf or legacy systems, the efficacy of automatic model-transformations in the context of optimisation and the scalability of models with respect to computational cost of analyses.

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