

SCARS: Suturing wounds due to conflicts between non-functional requirements in autonomous and robotic systems

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Abstract

In autonomous and robotic systems, the functional requirements (FRs) and non-functional requirements (NFRs) are gathered from multiple stakeholders. The different stakeholder requirements are associated with different components of the robotic system and with the contexts in which the system may operate. This aggregation of requirements from different sources (multiple stakeholders) often results in inconsistent or conflicting sets of requirements. Conflicts among NFRs for robotic systems heavily depend on features of actual execution contexts. It is essential to analyze the inconsistencies and conflicts among the requirements in the early planning phase to design the robotic systems in a systematic manner. In this work, we design and experimentally evaluate a framework, called SCARS, providing: (a) a domain-specific language extending the ROS2 Domain Specific Language (DSL) concepts by considering the different environmental contexts in which the system has to operate, (b) support to analyze their impact on NFRs, and (c) the computation of the optimal degree of NFR satisfaction that can be achieved within different system configurations. The effectiveness of SCARS has been validated on the iRobot® Create® 3 robot using Gazebo simulation.

KEYWORDS

autonomous systems, conflicts, contexts, non-functional requirements, optimization

1 | INTRODUCTION

Conflicts among functional and non-functional requirements for autonomous and robotic systems may leave open wounds (or scars) which may have disastrous effects when the system is put into operation. This work is intended to help developers handle such conflicts by providing appropriate relations specific to different contexts.

Abbreviations: FR, Functional requirement; NFRs, Non-functional requirements; QoS, Quality of service; ROS, Robotic operating system; SCARS, Specification framework for NFR conflict analysis in Robotic systems.

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Modern-day autonomous and robotic systems (like self-driving cars, industrial or healthcare robots, etc.) are so designed that they cater to the needs of multiple stakeholders and can self-adapt to changing environments (or contexts). The architecture of these systems is inherently complex due to the existence of multiple interacting hardware (like sensors, actuators, and microcontrollers) and software components (like data processing and route planning).¹ Each component has a set of associated functional goals that it can perform and a set of non-functional properties that it can strive to achieve (like response time, availability, and security). These components synchronize with each other to achieve higher-level goals or tasks in different environmental contexts. The functional and non-functional properties of these (heterogeneous) components require careful analysis in order to determine their compatibilities toward higher-level system goals. A change in the non-functional property of one component may have a severe effect on other components.² An additional level of complexity results from the need for autonomous and robotic systems to adopt different operational configurations under different environmental contexts.^{3,4} This switching to different configurations requires an understanding of how contexts affect different NFRs (like low illumination may require high robustness), conflicts among NFRs, (like between robustness and efficiency in low illumination is likely to be more than in normal conditions), and their priorities in different scenarios.⁵ Unlike generic software applications, autonomous and robotic systems are extremely safety-critical. Negligence of NFRs and their interactions with environmental contexts may cause system failures resulting in the loss of human lives.⁶ Thus the suitable operational configuration of the system in different contexts must be selected considering these factors.⁷ This highlights two important research objectives:

- Q-1 *How conflicts among NFRs associated with different usage contexts can be properly represented for autonomous and robotic systems?*
- Q-2 *How the requirements for autonomous and robotic systems can be analyzed in the specification phase to tune the parameters so that the system design can optimally match the actual environmental context?*

Formal specifications are well-known for providing non-ambiguous and consistent representations of hardware and software systems.^{8,9} Autonomous and robotic systems require different concepts and notations that are generally different from other general domains. In the existing state of the art, several metamodels¹⁰ have been proposed for modeling robotic systems. Most of the meta-models proposed for autonomous and robotic systems are limited to capturing only some of the concepts and notations for robotic systems. There are works^{7,11} that have tried to capture the non-functional properties of autonomous and robotic systems. However, these are often not quite generic and are applicable to specific NFRs only. The existing meta-models, devised for the purpose, hardly consider any analysis of important issues including conflicts among the NFRs, the impact of environmental contexts on system performance, and so forth.

Thus the existing state of the art highlights the necessity of providing solutions for the research issues mentioned in Q-1 and Q-2. Owing to the critical nature of the robotics systems, it is necessary to have a comprehensive formal specification framework that would be capable of capturing all possible concepts and notations required for designing the robotic system. Further, such a framework needs to analyze NFRs in different contexts, identify inter-NFR conflicts, and evaluate the optimal system designs, so that it can adapt to different environmental contexts. In this work, we attempted to address the research issues by introducing an operational framework SCARS. The SCARS framework handles requirement conflicts and consistency issues for robotic systems in the requirement engineering phase. The outcome of this framework might help the system architects to make appropriate design decisions.

The operational framework, named SCARS (Specification Framework for NFR Conflict Analysis in Robotic Systems), operates in three stages:

1. *System and scenario specification*: A domain-specific language (DSL) is introduced to support a context-aware specification of ROS²*-based robotic autonomous systems. The requirement analysts, in conjunction with the system designers, specify all concepts associated with their robotic and autonomous system using the proposed DSL. The proposed DSL metamodel has been developed on the MPS[†] framework.
2. *Requirement analysis*: The domain-specific requirements specified using the proposed DSL are then subjected to different analyses that can identify inconsistencies, incompatibilities and conflicts among the requirements. The requirements are analyzed in different contexts, by identifying the risks associated with conflicting NFRs. We have used the in-built model checker in MPS to implement the different types of analyses.

*<https://www.ros.org>.

†<https://www.jetbrains.com/mps/>.

3. *NFR optimization*: In the final stage, our framework derives the optimum satisfaction values of each NFR in different contexts, given their conflicts and association with different FRs. These values help the system designers in choosing the appropriate software operationalizations to fulfill those NFRs while minimizing the risk of system refactoring and failures in the future.

Stage 1 addresses the first research objective Q-1 by explicitly capturing contexts NFR correlation using the proposed DSL. Stages 2 and 3 addresses the second research objective Q-2 where requirements are analyzed and optimal non-functional properties in different contexts are determined.

As a proof of concept, we have used the Create[®] 3 robot[‡] simulator for conducting experiments. The objective of these experiments is to assess the whole procedure and to validate the optimal satisfaction values generated by SCARS.

The main contribution of this research work is the proposed SCARS framework that not only provides a generic structure for specification but also conflict analysis of NFRs. The proposed DSL metamodel is built on top of the ROS2 DSL concepts already proposed in the literature. Reusing concepts ensures backward compatibility. The proposed DSL metamodel can be adapted for other types of autonomous systems in general with minimal changes, as the classes defined in the metamodel are also applicable to other autonomous systems.

The rest of the paper is structured as follows. Section 2 elaborates on the existing state-of-the-art. Section 3 recalls some preliminary notions that will help the reader to better understand the work. Section 4 explains the proposed SCARS framework. Section 5 discusses the experiments. Section 6 highlights the different threats to the validity of this work. Section 7 concludes and discusses possible future work.

2 | RELATED WORK

General-purpose modeling languages are well-known for system specifications. However, researchers in the robotics community have widely adopted DSL for system specifications.¹⁰ To frame our contribution in the current research context, we first discuss the different metamodels and domain-specific languages for robotic systems; we then discuss the different formal analysis approaches in the literature, and finally, we discuss the different NFR conflict analysis approaches that have been proposed so far.

2.1 | Metamodels and DSL

Researchers in Reference 12 have proposed a domain-specific modeling language known as RoBMEX for the specification of drone missions. RoBMEX consists of three metamodels- one metamodel for ROS systems (ROSPromL), another for general-purpose operations using ROS variables (RosModL), and the third one for drone missions (ROSMiLan). Authors in Reference 13 have presented RoboChart, a domain-specific modeling language based on UML for robotic applications. RoboChart is supported by RoboTool which enables modeling, performs type checking and analysis of well-formedness, and automatically calculates CSP models. It helps to capture robotic platforms, parallel controllers and machines' synchronous and asynchronous communications. In Reference 14, a domain-specific language called RobotML suitable to specify missions, environments and robot behaviors has been proposed. The DSL aims to ease the definition of specific robotic architecture (reactive, deliberative, hybrid) and specific components that form the architecture (sensors, actuators, planners, mapping, etc.). The communication mechanisms between components (sending/receiving of event notifications and data) are also captured in this framework.

In Reference 11 authors have proposed a formal specification framework known as Self Adaptive Framework for Robotic Systems (SafeRobots). It proposes two models: (1) a functional model capturing behavioral or functional requirements that specify the inputs (stimuli) to the system, the outputs (response) from the system, and the behavioral relationships between them, (2) a non-functional model for specifying non-functional aspects or quality claims of the system. In Reference 7 authors have proposed an Eclipse-based metamodel known as RoQME. RoQME defines two meta-models: (1) the RoQME meta-model, responsible for the definition of Non-Functional Properties, contexts and Observations; and (2) the RoQME-to-RobMoSys mapping meta-model, responsible for binding each context defined in a RoQME model with the RobMoSys Service Definition acting as the corresponding context provider. Researchers in

[‡]https://iroboteducation.github.io/create3_docs/.

Reference 15 have proposed a domain-specific language (DSL) that allows domain experts to specify (i) quality of service (QoS) requirements of the communication channels; and (ii) QoS capabilities of the software components in robotic systems. They have developed ROS 2 based DSL and also allow to verify the QoS specification for any incompatibility. Authors in Reference 16 have argued that most languages for human-machine systems provide support for functional behavior, while non-functional properties are specified through informal comments. They have proposed a metamodel for modeling non-functional aspects of both human and machine models. In Reference 17 authors have provided an extension of the UML MARTE profile for modeling and quantitative analysis of robotic-specific non-functional requirements. The extended UML MARTE profile is used for modeling safety properties for a robot navigation system.

SysML[§] requirements module is used to capture requirements, the relations between them and their relationship to other model elements. The relationships that can be modeled between the requirements are *derive*, *namespace*, *copy* and *refine*. These relationships capture how one requirement may be derived, contained or refined from another requirement. SysML Block diagram captures different hardware, and software components as structural units embedding their properties, behaviors and constraints. Researchers have used SysML with DSL notations for autonomous system specifications. Authors in Reference 18 proposed a SysML-based approach for traceability modeling of requirements in UAV command system-of-systems. Authors in Reference 19 have proposed a new SysML-based modeling language UavSwarmML for specifying swarm missions of autonomous aerial robots. Researchers in Reference 20 proposed a new SysML profile (Systems Modeling Language) developed using DSL (Domain Specific Language) to include Robot Operating System (ROS2) objects and attributes.

Most of the DSL or metamodels proposed in the literature are aimed toward representing the robot behaviors (functional behaviors). There are limited works that have tried to capture different components (different categories of hardware components) of these systems. Existing literature does not explore how the functional and non-functional properties of components are related especially when they operate together to achieve a higher-level goal or task. Also, we find that there is a lack of a generic framework that can model NFR concerns specific to robotic systems and their inter-relationships in particular.

2.2 | Requirements analysis

Researchers in Reference 21 used behavior trees to describe a particular task scenario (or functional goals) for robots. The behavior tree is further mapped to HFSM (Hierarchical Finite State Machine) and the temporal properties are verified using NuSMV. This framework also automates code generation and does runtime monitoring of those properties as well. ForSAMARA[¶] is another project where authors have specified robot skills using behavior trees. These are then converted to a model that can be verified. It uses Octomap to simulate environments in which the robots may operate. The model and the map are then fed into the model checker along with safety properties (specified using LTL) to be verified. Authors in Reference 22 have proposed a tool named LTLMoP which includes a parser that automatically translates English sentences belonging to a defined grammar into LTL formulas. This grammar can capture robot behavior and the environment in which it can operate. A task that is captured using an LTL formula, is synthesized into an automaton. It builds an automaton from the specification as long as the assumptions regarding the environment hold true. In Reference 23 a new specification language (LTL based) for reactive systems has been proposed. It comes with the Spectra Tools,²³ to perform analyses, including a synthesizer to obtain a correct-by-construction implementation, and also additional analyses aimed at helping engineers write higher-quality specifications. Starting with the formal specifications, it analyses if it is realizable and generates the state machine. If the state machine is not realizable then there may be conflicting safety and liveness properties.

In Reference 24, the author has reviewed different NFRs specific to robotic systems: how they are modeled and analyzed in the run-time environment? The author has highlighted that existing state-of-the-art focuses only on some specific NFRs in specific environments. The challenge lies in combining heterogeneous models that analyze different non-functional properties. The author has also highlighted how conflicts among NFRs are not addressed in these works. Authors in Reference 9 have surveyed the state of the art in formal specification and verification for autonomous robotics and the challenges posed. In Reference 5, authors have discussed the need for system reconfiguration arising

[§]<https://sysml.org/>.

[¶]ForSAMARA—Formal safety analysis in modular robotic applications is cascaded funded by European Horizon2020 project RobMoSys (grant agreement No. 732410).

out of the relationship between NFRs and the environmental context for autonomous systems. In Reference 25, authors have studied how unpredictable environments may lead to violation of non-functional properties in robots. They have suggested self-adaptation strategies to solve this problem. HAROS[#] framework is another category of work where quality assurance of robotic software is done using static analysis. It performs design checks for robotic software from a middleware perspective.

2.3 | NFR conflict analysis

NFRs impact the satisfaction (or denial) of other NFRs very frequently. An NFR conflict is identified as a situation where the fulfillment of two NFRs contradicts each other²⁶ that is, realizing one NFR has a negative impact on the fulfillment of another NFR. Most of the proposed NFR conflict identification approaches in the literature are based on either heuristics or ontology. Heuristic conflict identification approaches are mostly explored in literature and has resulted in creating a knowledge base (conflict catalog^{27,28}) that can be used by industry experts in system design. Ontology-based approaches are focussed on creating different categories of ontologies and provide different conflict detection rules.²⁹ Catalog-based approaches for NFR analysis are found to be more useful.^{30,31} In Reference 23, authors have tried to address the issue of conflicts among NFRs in robotic systems. They have provided a conflict resolution approach based on a weighted sum. However, their conflict resolution is not generic and limited to resolving between time and other non-functional properties only. Authors in Reference 32 have discussed NFRs of ubiquitous and IOT applications. They have highlighted conflicts among these particular NFRs. Researchers in Reference 33 have evaluated different NFRs that are of concern for IOT applications. There are limited works^{23,24} in the existing state of the art that have tried to analyze conflicts among the NFRs specific to robotic autonomous systems.

Table 1 provides a detailed comparison of some of the formal approaches for robotic autonomous systems. The table includes only those works that have at least provided a metamodel or DSL in their proposal.

3 | PRELIMINARIES

This section explains some of the preliminary concepts that may be helpful for the readers to better understand the proposed framework and design challenges for robotic systems.

3.1 | Concepts

1. Non-functional requirements of robotic systems

Autonomous systems in particular robotic systems consist of certain specific NFRs of concern like safety, transparency and fairness. Several studies have been conducted in the literature that have listed out the NFRs concerned with these systems.^{24,33}

Typically, NFRs are classified into two broad categories:³⁴ (1) Architectural NFRs and (2) Run-time NFRs. Architectural NFRs are those that are not directly measurable from the system's operational environment. They are more of a design issue. Run-time NFRs are those that can be directly measured from the system's operational environment by observing the performance characteristics. In this research work, we have limited our focus only to run-time NFRs, as they are measurable both qualitatively and quantitatively. The document provided at^{||} shows the NFR categorization as architectural and run-time NFRs. Each of these run-time NFRs is expressed in terms of one or more metrics.²⁶ However, there are some run-time NFRs for which no specific metrics have been defined in the literature. Keeping this in mind, we have further refined our run-time NFR list to contain only those NFRs that have a well-defined metric associated with them (refer to note^{||}).

The run-time NFRs being considered can be further classified into the following two categories:

[#]<https://github.com/git-afsantos/haros>.

^{||}https://github.com/RESSA-ROB/SCARS/blob/main/NFR_Catalog.pdf.

TABLE 1 Qualitative comparison with existing works.

Research work	Metamodel concepts				Requirements Analysis						
	ROS-based	Components (atomic and composite)	Communication among components	Communication QoS parameters	FRs	NFRs	FR-NFR dependency	Context-NFR correlation	NFR conflict	Temporal property	Communication QoS compatibility
Ramaswamy et al. ¹¹	Mentioned	Included	Included	Not mentioned	Included	Included	Included	Not mentioned	Not mentioned	Not mentioned	Not mentioned
Parra et al. ¹⁵	Mentioned	Included	Included	Included	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Included
Ladeira et al. ¹²	Mentioned	Included	Included	Not mentioned	Included	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned
Miyazawa et al. ¹³	Mentioned	Included	Not mentioned	Not mentioned	Included	Temporal NFRs only	Not mentioned	Not mentioned	Not mentioned	Included	Not mentioned
Cristina et al. ⁷	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Included	Not mentioned	Included	Not mentioned	Not mentioned	Not mentioned
Dhouib et al. ¹⁴	OROCOS based	Included	Included	Not mentioned	Included	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned
Brugali ¹⁷	Not mentioned	Included	Included	Not mentioned	Included	Included	Not mentioned	Included	Not mentioned	Not mentioned	Not mentioned

- a. *Optimistic low (C-1)*: We assign those NFRs to this category for which a lower value of the associated metric implies better satisfaction of the NFR. For example, NFRs like response time and cost, are optimistic toward minimum value that is, lower the response time of the system better is the system performance.
 - b. *Optimistic high (C-2)*: We assign those NFRs to this category for which a higher value of the associated metric implies better satisfaction of the NFR. For example, NFRs like accuracy and availability, is optimistic toward maximum value that is, higher the availability of the system more reliable it becomes.
2. **NFR conflict identification**
As NFR conflict knowledge base for autonomous systems in particular robotic systems we rely on data collected from the existing literature (namely, References 27,28,32,33,35–38) and by collating knowledge from domain experts. The document provided at contains the NFR conflict catalog that we have built and used in this research work.
 3. **QoS policies**
Quality of service policies allows us to tune communication between nodes. ROS2 has defined several QoS policies** for the communicating nodes. In the definitions, of the QoS policies a *publisher* refers to the node sending a message or data and a *subscriber* refers to the node receiving a message or data. The QoS policies can be captured in the proposed DSL metamodel.

3.2 | Challenges in the design of robotic autonomous system

Autonomous systems in particular robotic systems consist of various nodes deployed internally or externally that coordinate and exchange data to execute some tasks. The components of these systems belong to two categories (i) operational components (hardware and software) and (ii) communication components. These components are associated with several constraints like NFRs, dependency (between FR and NFR), compliance with standards, scenario constraints and others. Such a component-based system that has a variety of operational tasks, non-functional properties and communication channels gives rise to the following concerns or issues:

- I-1 **Intra NFR conflict**: *Whether the non-functional properties of a component are in conflict? If they are in conflict how they can be operationalized so that all required priorities are met?*
- I-2 **Inter NFR conflict**: *Whether there exist conflicts among the non-functional properties of a group of components (like a swarm of robots or a group of heterogeneous components) when they are deployed in a particular environment?*
- I-3 **NFR compliance**: *How compliance of NFRs with standards can be ensured at design time?*
- I-4 **Context-NFR correlation**: *How the satisfiability of non-functional properties of the system are affected in different contexts?*
- I-5 **QoS compatibility**: *Whether communicating nodes have a compatible set of QoS policies?*

These issues are related to the research objective (Q-2). Each of these issues involves different analyses of the system specification. The SCARS framework addresses in particular the issues I-1, I-2, I-4 and I-5 above.

4 | THE PROPOSED APPROACH

This section illustrates the proposed DSL metamodel and the SCARS framework in detail.

4.1 | The DSL metamodel

The proposed DSL metamodel is depicted in Figure 1, consisting of three categories of artifacts: (i) Operational Artifacts (ii) Communication Artifacts and (iii) Constraints. It is to be noted that operational and communication artifacts have already been proposed in the literature in different forms. However, a single DSL metamodel in the literature does not consist of all the artifacts together. We introduce the constraints as the new artifact for making NFR conflicts and inconsistencies in different environmental contexts explicit. Each of these artifacts consists of one or more classes. The concepts (or class) of the DSL metamodel are further illustrated using examples created on the MPS platform.

**<https://docs.ros.org/en/rolling/Concepts/About-Quality-of-Service-Settings.html>.

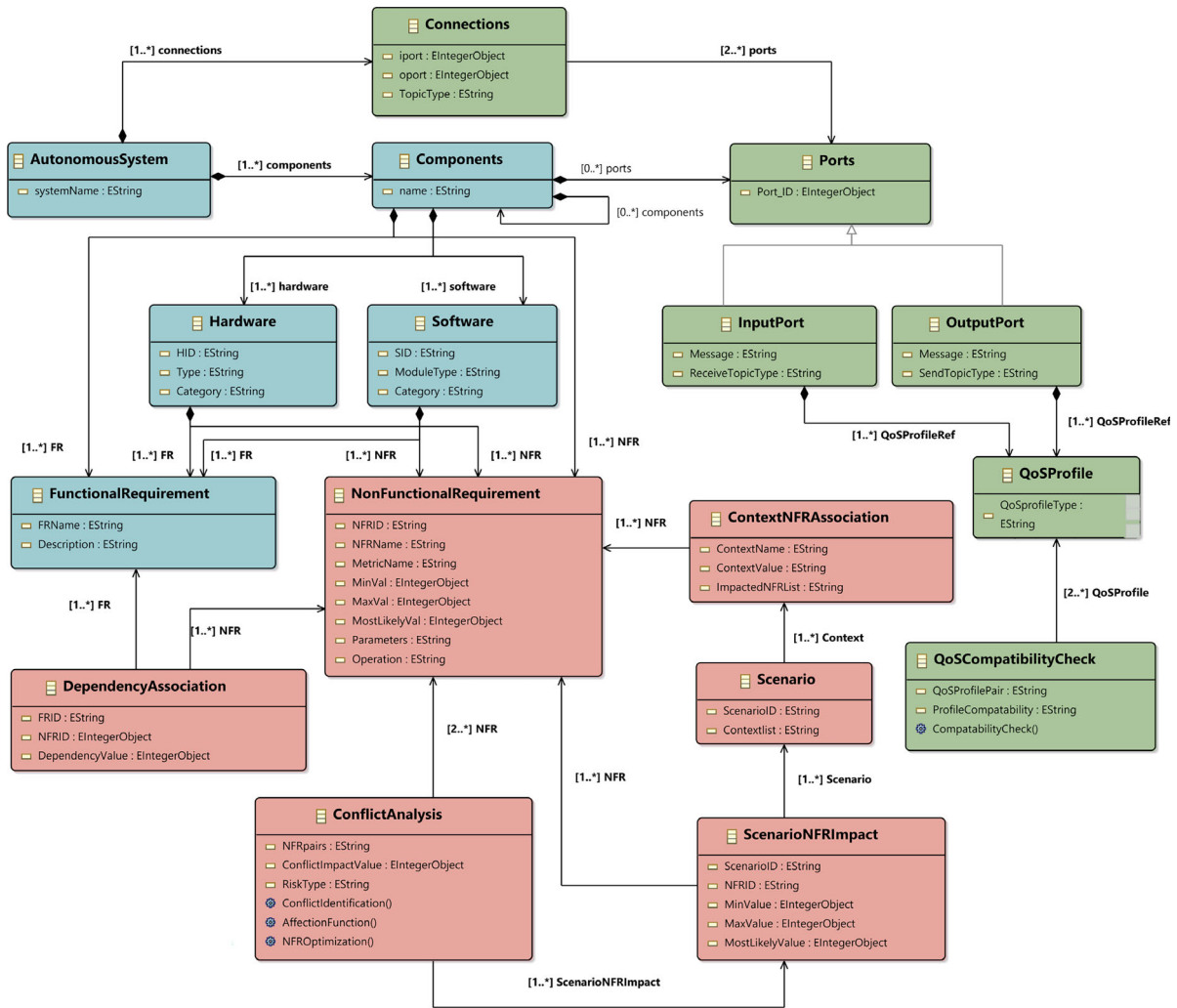


FIGURE 1 DSL metamodel.

1. **Operational artifacts:** The classes representing the operational artifacts are as follows (marked in blue in Figure 1):
 - a. **AutonomousSystem** is the root class of the metamodel. Its instances are characterized by a *systemName* that can be used to refer to the domain where robots are deployed. For example the class **AutonomousSystem** can represent a Hospital where a swarm of robots are deployed.
 - b. **Components** class represents the different components of robotic autonomous systems. Each instance of **Components** class has a *Name*. The **Components** class can represent composite components of the system. Hence each artifact that is defined using **Components** class, consists of one or more sub-components. These sub-components can again be composite (defined using **Components** class) or atomic (defined using **Hardware** or **Software** class). The **AutonomousSystem** class is composed of one or more **Components**.
 - c. The **Components** class is composed of two subclasses **Hardware** and **Software**. The **Hardware** and **Software** classes are used to represent atomic components.
 - d. The instances of **Hardware** class are characterized by its *HID* (a unique identifier), *Type* (represent the type of the device which may be sensors or actuators), and *Category* (captures the class of devices mechanical or electrical part).
 - e. The instances of **Software** class are characterized by its *SID* (a unique identifier), *ModuleType* (that may be connectivity, power management) and *Category* (captures the class of software like operating system or user interface).

Devices like cameras and actuators can be defined as atomic components (using **Hardware** class) or as composite components (using **Components** class). This depends upon the level of detail the system engineers need

TABLE 2 Examples of operational artifacts.

Operational artifacts	
Example 1	Component Name: ROBOT1 Sub Components CAM1 CAM2 Hardware Components Actuator: Robot Wheel Sensor: H1 Controller: H103 Software Components Path Planner Functional Objective FR Name: Fetch Description: Fetch clothes from the racks. FR Name: Deliver Description: Deliver clothes to the washer.
Example 2	Component Name: CAM2 Sub Components << ... >> Hardware Components Sensor: Lens 1.2 Software Components Motion Detector Functional Objective FR Name: Object Capture Description: Records objects even in low illumination.
Example 3	Hardware component: Robot Wheel Type: Actuator Category: Mechanical HID: W101 Functional Objective FR Name: Rotation Description: Wheels should rotate 360 degrees.

to capture. Example 2 in Table 2, a camera is defined as a composite component. Example 3 in Table 2, a wheel (actuator) is defined as an atomic component. CAM2 and Robot Wheel are the components referred in the specification of ROBOT1 in Example 1.

- f. The `FunctionalRequirement` class captures the FRs. The instances of `FunctionalRequirement` are characterized by their *FRName* (identifier for a functional requirement) and *Description*. The `Hardware`, `Software` and `Components` classes are composed of class `FunctionalRequirement`. The functional goals of each atomic and composite component can be captured in the DSL metamodel. Example 1 and Example 3 in Table 2 show some sample FRs of a robot and a wheel, respectively.
2. *Communication artifacts*: The classes representing the communication artifacts are as follows (marked in green in Figure 1):

- a. The `Ports` class is used for representing communication ports. The `Components` class is also composed of one or more `Ports`. Each instance of `Ports` class is characterized by a `Port_ID`. The attribute `Port_ID` represents a unique identification number of each port.
- b. The `Ports` class is a supertype for two subclasses `InputPort` and `OutputPort`.
- c. The instances of `InputPort` are characterized by the attributes–`Message` (data/message component receives) and `ReceiveTopicType` (type of message received, for example traffic alert, object detection).
- d. The instances of `OutputPort` are characterized by the attributes–`Message` (data/message component sends) and `SendTopicType` (type of message send).

We have pre-defined some of the plausible topic types¹⁵ while implementing the language model in MPS. The designer can select a topic from the list while creating a specification. This list can be extended as required. Example 4 in Table 3 shows a component's sample input and output port specification.

TABLE 3 Examples of communication artifacts.

Communication artifacts	
Example 4	(Input Port) ID → IN101 Receive Topic Type: Location Message: Object Detected. QoS Profile: Check3 QoS Profile Type: Location (Output Port) ID → OT101 Send Topic Type: Warnings Message: Failed to complete tasks. QoS Profile: Check1 QoS Profile Type: Warnings
Example 5	Connections Topic Type: Location OT102 → IN105 Topic Type: Warnings OT101 → IN108
Example 6	Policy List: Check1 QoS Profile Type: Warnings Reliability == RELIABLE Durability == TRANSIENT_LOCAL Liveliness == MANUAL_BY_TOPIC Deadline == 12 Lease Duration == 10 Policy List: Check2 QoS Profile Type: Traffic Reliability == BEST_EFFORT Durability == VOLATILE Liveliness == AUTOMATIC Deadline == 15 Lease Duration == 12 Policy List: Check3 QoS Profile Type: Location Reliability == RELIABLE Deadline == 7

- e. The `Connections` class defines how the information flow occurs between the ports of one device to another. The instances of this class are associated with attributes *iport* (refers to input ports), *oport* (refers to output ports) and *TopicType* (records the type of data exchanged). Each instance of `Connections` class defines data flow from an output port to an input port. The `AutonomousSystem` class is composed of one or more connections. For instance, Example 5 in Table 3 shows connections defined between pairs of ports. Each connection also includes the type of data exchanged between the ports.
 - f. The `QoSProfile` class represents the different quality of service parameters associated with communicating nodes. Each instance of `QoSProfile` consists of *QoSprofileType* (this profile type corresponds to the different topics of input and output ports) and *policyList* (list of QoS policies). The specification of *QoSprofileType* is significant as the exchange of different information may require different QoS parameters. The `InputPort` and `OutputPort` classes are associated with one or more `QoSProfile` classes. Example 6 in Table 3 shows how QoS policies are captured in the proposed DSL. Each QoS policy has a type associated with it. The type of `InputPort` and `OutputPort` that is, attributes *ReceiveTopicType* and *SendTopicType* respectively, must match the type of QoS profile (attribute *QoSprofileType*) assigned to it (as shown in Example 4 in Table 3).
 - g. The `QoSCompatibilityCheck` class captures the compatibility issues between different QoS profiles. The instances of this class are characterized by the attributes *QoSProfilePair* (QoS profiles whose policies are incompatible) and *ProfileCompatibility* (records the compatibility issues). The `QoSCompatibilityCheck` class consists of the `CompatibilityCheck()` function that checks for the compatibility of QoS profiles associated with different ports that communicate to exchange data. The `CompatibilityCheck()` method refers to the QoS compatibility rules defined for ROS2^h.
3. *Constraints*: We have defined several constraints as classes in the metamodel (marked in red in Figure 1).
 - a. The `NonFunctionalRequirement` class captures the NFRs associated with operational artifacts. The instances of `NonFunctionalRequirement` class are characterized by the following attributes:
 - (i) *NFRID*: A unique identifier.
 - (ii) *NFRName*: It represents the NFR category, such as security.
 - (iii) *MetricName*: Captures different metrics that are associated with each NFR category, such as encryption level for security.
 - (iv) *MinVal*: Represents minimum value of an NFR.
 - (v) *MaxVal*: Represents maximum value of an NFR.
 - (vi) *MostLikelyVal*: Represents the most likely value of an NFR.
 - (vii) *Parameters*: It captures other NFRs on which a particular NFR is dependent. This is applicable mostly in the case of composite components that are made up of several sub-components (atomic or composite). The satisfaction of the NFR of a high-level composite component may be dependent on the NFRs of its sub-components.
 - (viii) *Operation*: It specifies how the NFRs of lower-level sub-components are related to the NFR of the higher-level component.
The minimum, maximum and most likely values are expected to be provided by the requirement analyst. The domain of these values depends on the individual NFR category (refer to Example 11 in Table 4). When these values are used in computations they are normalized in the same scale. The `Hardware`, `Software` and `Components` classes are composed of class `NonFunctionalRequirement`. Example 7 in Table 4 shows the NFRs defined for component `ROBOT1` of Example 1 in Table 2. The NFR `N601` is related to two NFRs `N101` and `N301` and the operation is `max`. Then the maximum of the *most likely* values of these two NFRs must match with the *most likely* value of NFR `N601`.
 - b. The `DependencyAssociation` class is used to capture the associations between `FunctionalRequirement` and `NonFunctionalRequirement`. NFRs are feature-centric.³⁹ The `DependencyAssociation` class captures relevant NFRs associated with functional features that are required to be satisfied. Specification of NFRs for each functionality ensures that it is realized in such a manner that the required non-functional properties can be satisfied. Also, it can be used to verify whether the deployed system meets or violates non-functional properties. The instances of `DependencyAssociation` class are characterized by *FRID*, *NFRID* and *DependencyValue*. The attributes *FRID* and *NFRID* refers to the attributes *FRName* and *NFRID* of `FunctionalRequirement` and `NonFunctionalRequirement` class respectively. The *DependencyValue* represents the degree of dependency

TABLE 4 Examples of constraints.

Constraints	
Example 7	<p>Non-functional objective</p> <p>Non-functional property</p> <p>ID: N601</p> <p>NFR category: Availability -></p> <p>Metric: Probability percentage of system uptime</p> <p>Minimum value: 70 Maximum value: 90</p> <p>Most likely value: 85</p> <p>Parameters: N101 NFR category: Availability -></p> <p>Metric: Probability percentage of system uptime</p> <p>N301 NFR category: Availability -></p> <p>Metric: Probability percentage of system uptime</p> <p>Operation</p> <p>Max</p> <p>Non-functional property</p> <p>ID: N602</p> <p>NFR category: Performance -></p> <p>Metric: Response time</p> <p>Minimum value: 2 Maximum value: 10</p> <p>Most likely value: 5</p> <p>Parameters</p> <p><< ... >></p> <p>Operation</p> <p><< ... >></p>
Example 8	<p>Deliver->N601 NFR category</p> <p>Availability ->Metric: Probability percentage of system uptime</p> <p>Dependency value: 8</p> <p>Deliver->N602 NFR category</p> <p>Performance ->Metric: Response time</p> <p>Dependency value: 9</p> <p>Fetch->N601 NFR category</p> <p>Availability ->metric: Probability percentage of system uptime</p> <p>Dependency value: 8</p> <p>Fetch->N602 NFR category</p> <p>Performance ->metric: Response time</p> <p>Dependency value: 6</p>

(Continues)

TABLE 4 (Continued)

Constraints	
Example 9	Contexts-NFR association ID: C1 Name: Lightning values: Dim Impacted NFR: N601 NFR category Availability →metric: Probability percentage of system uptime N602 NFR category Performance →metric: Response time Contexts-NFR association ID: C2 crowd: Low Impacted NFR: N601 NFR category Availability →metric: Probability percentage of system uptime N602 NFR category Performance →metric: Response time Contexts-NFR association ID: C3 name: Crowd: Heavy Impacted NFR: N601 NFR category Availability →metric: Probability percentage of system uptime N602 NFR category Performance →metric: Response time
Example 10	Scenario Scenario ID: S1 Contexts-C1-Lightning: Dim, C2-Crowd: Low Scenario ID: S2 Contexts: C1-Lightning: Dim, C3-Crowd: Medium
Example 11	Scenario-NFR impact Scenario ID: S1 NFR: N601 NFR category Availability →metric: Probability percentage of system uptime Min value: 60 max value: 80 Most likely value: 70 Scenario ID: S2 NFR: N602 NFR category Performance →metric: Response time Min value: 5 max value: 10 Most likely value: 7

between FRs and NFRs. The domain of `DependencyValue` is within 1–10, in our framework. These associations are expected to be identified by the requirement analyst⁴⁰ using existing frameworks like Reference 41. `DependencyValue` is further used for deriving optimum satisfaction values of NFRs. Example 8 in Table 4 shows an association among the NFRs of Example 7 with the FRs defined in Example 1 for the component `ROBOT1`.

c. The `ConflictAnalysis` class captures the conflict relationship between different `NonFunctionalRequirement`. The instances of this class consist of the following attributes:

- (i) *NFRpairs*: The pair of NFRs that are identified to be in conflict by the `ConflictIdentification()` function.
- (ii) *ConflictImpactvalue*: The degree of conflict among NFRs. The impact values can be of three types: *linear*, *polynomial* and *exponential*.
- (iii) *RiskType*: The risk imposed by each identified conflict. the risk can be: *low*, *moderate*, *high*.

The `ConflictAnalysis` class also consists of three functions:

- (i) `ConflictIdentification()`: Identifies pair-wise conflict among NFRs.
- (ii) `AffectionFunction()`: It derives the degree of conflict and risk involved.
- (iii) `NFROptimization()`: It derives an optimized satisfiability value of each NFR in conflict.

- d. The class `ContextNFRAssociation` is used to represent the different environmental contexts and correlates these contexts with NFRs. The context represents environmental conditions in which system has to operate. The instance of this class is characterized by the *ContextName*, *ContextValue* and *ImpactedNFRList*. The attribute *ContextName* and *ContextValue* defines an environmental context and its label respectively. The attribute *ImpactedNFRList* lists the different non-functional properties that may get affected in a particular context. Example 9 in Table 4 shows instances of sample contexts and impacted NFRs as defined in MPS platform.
- e. The `Scenario` class in the metamodel is used to represent different scenarios in which the system has to operate. Its instances are characterized by the *ScenarioID* and *ContextList* (that is inherited from `ContextNFRAssociation` class). Each scenario is a combination of multiple environmental contexts. The attribute *ContextList* consists of the set of contexts that makes up a particular scenario. Example 10 in Table 4 shows how the contexts of Example 9 are combined to create different scenarios.
- f. The class `ScenarioNFRImpact` captures how multiple contexts when occur together affects different non-functional properties of the system. Its instances are characterized by the following attributes: *ScenarioID*, *NFRID* (this NFRs must match with the one defined with the contexts for a particular scenario), *MinValue*, *MaxValue* and *MostLikelyValue*. The parameters *MinValue*, *MaxValue* and *MostLikelyValue* capture how the NFR values may undergo changes for a particular scenario. This class addresses the issue I-4 mentioned in Section 3.2.

Example 11 in Table 4 shows the correlation between NFRs and scenarios. The NFR N601 that was defined earlier in Example 7 in Table 4 undergoes a change in its specification in scenario S1 in Example 11. These correlations are to be determined by system analysts manually.

4.2 | The SCARS framework

This section illustrates the overall workflow and different modules of SCARS (refer to Figure 2). We assume that the following conditions are satisfied:

1. The availability of conflict catalogs (based on state-of-the-art literature). These catalogs must include conflicts between NFRs specific to the robotic autonomous system (refer to note^{||}).
2. The availability of a QoS policy list for the system under consideration.
3. Relevant data on the environmental contexts under which the system shall operate.

The architecture of SCARS is shown in Figure 2. The end-to-end flow of activities is shown using solid arrows. The dotted arrows represent some of the optional activities that can be performed by the system designer. The architecture is partitioned into three modules, namely: (A) SYSTEM AND SCENARIO SPECIFICATION (B) REQUIREMENTS ANALYSIS and (C) NFR OPTIMIZATION. The following subsections illustrate each module in detail.

4.2.1 | SYSTEM AND SCENARIO SPECIFICATION

This module consists of two activities: (1) Requirement Specification using the DSL metamodel; and (2) Integration of scenario constraints in the requirement specification. The requirement engineer will use the DSL metamodel (described earlier) to generate a general requirement specification for the target system. This specification is then embedded with scenario specific constraints.

Integration of scenario constraints in the requirement specifications

The system specification must include the different scenarios (`Scenario` constraints in Figure 2) in which the system has to operate and how in different scenarios the non-functional properties of the system are affected (refer to Example 11 in Table 4). These scenario information will be obtained from different stakeholders of the system. The *Integration and Duplication* process in the framework takes the general requirement specification of the target system and augments them with scenario information. That is for each scenario a scenario-specific requirement specification is created and fed into the subsequent processes of the framework. Suppose, if there are n scenarios in which the system has to operate, our framework creates n separate requirement set (one for each scenario) for further analysis (refer to Figure 2). The objective

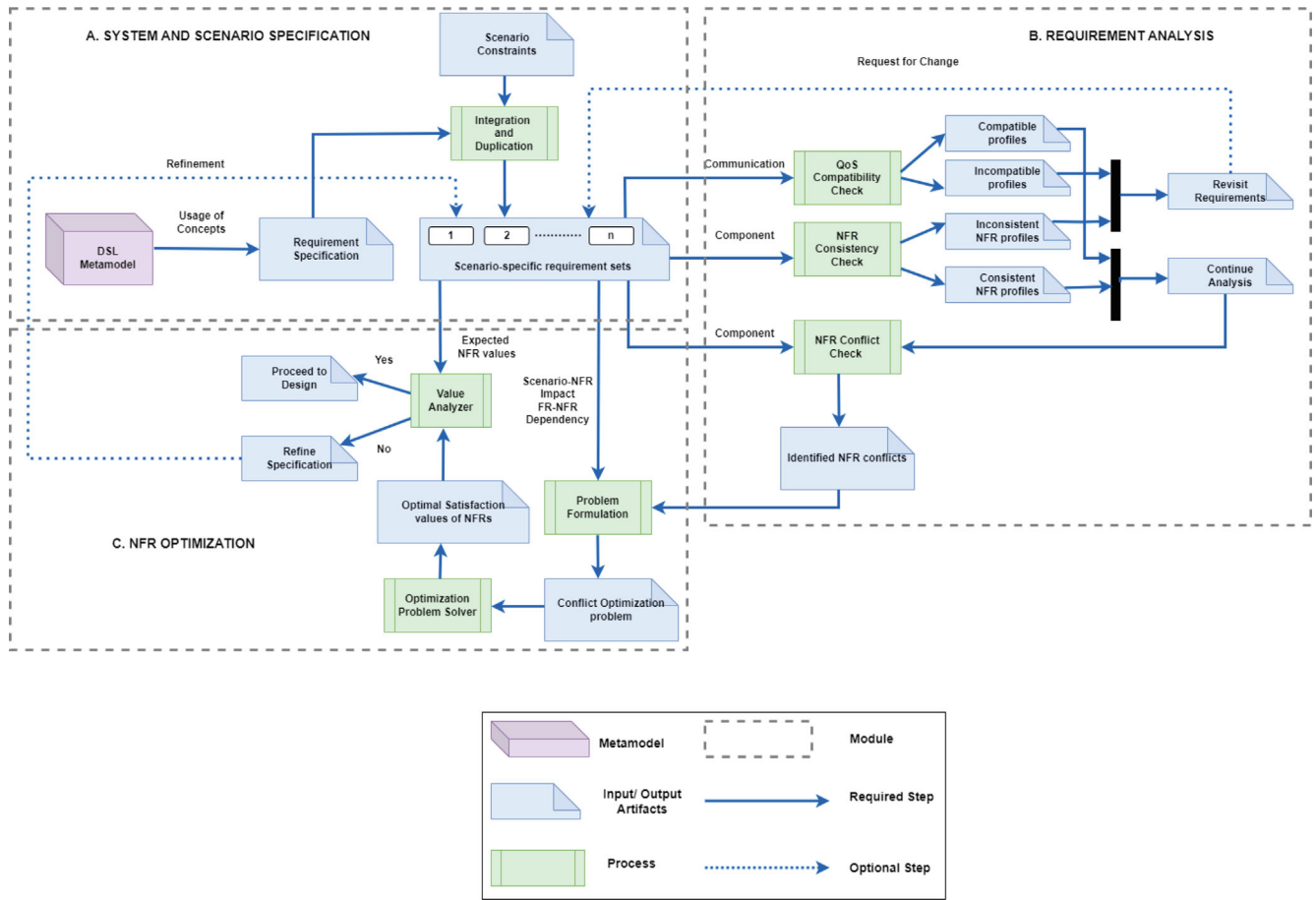


FIGURE 2 The SCARS framework.

of doing this is to separately check the risk factors (conflicts, inconsistencies) associated with different scenarios. This will assist the system designer to build various configurations of the system with minimum risk. In Example 11 there are two different scenarios. Each scenario has some effect on the non-functional properties that were specified in Example 7. Hence the *Integration and Duplication* process creates two separate scenario-specific requirement specifications (say R1 and R2). In requirement specification, R1 the specification of NFR N601 will be replaced with the one mentioned for scenario S1 in Example 11. In R1 specification of NFR N602 will remain the same as in Example 7. In requirement specification, R2 the specification of NFR N602 will be replaced with the one mentioned for scenario S2 in Example 11. In R2 specification of NFR N601 will remain the same as in Example 7.

It is to be noted that each scenario can impact multiple NFRs. In our examples, we have shown only a single instance for simplicity. In requirement sets R1 and R2 only NFR specification of different components is changed. Figure 3 shows the FRs and NFRs description for ROBOT1 in scenarios S1 and S2.

4.2.2 | REQUIREMENT ANALYSIS

In this module, each of the scenario-specific requirement specifications is subjected to analyses. It includes three different processes that check for incompatibilities, inconsistencies and conflicts in the requirement sets respectively. These processes can be executed in parallel and are explained in the following subsections.

QoS compatibility check

The management of QoS policies is an important aspect of an autonomous system as different devices communicate among themselves to publish and subscribe to information. The quality parameters associated with the communication

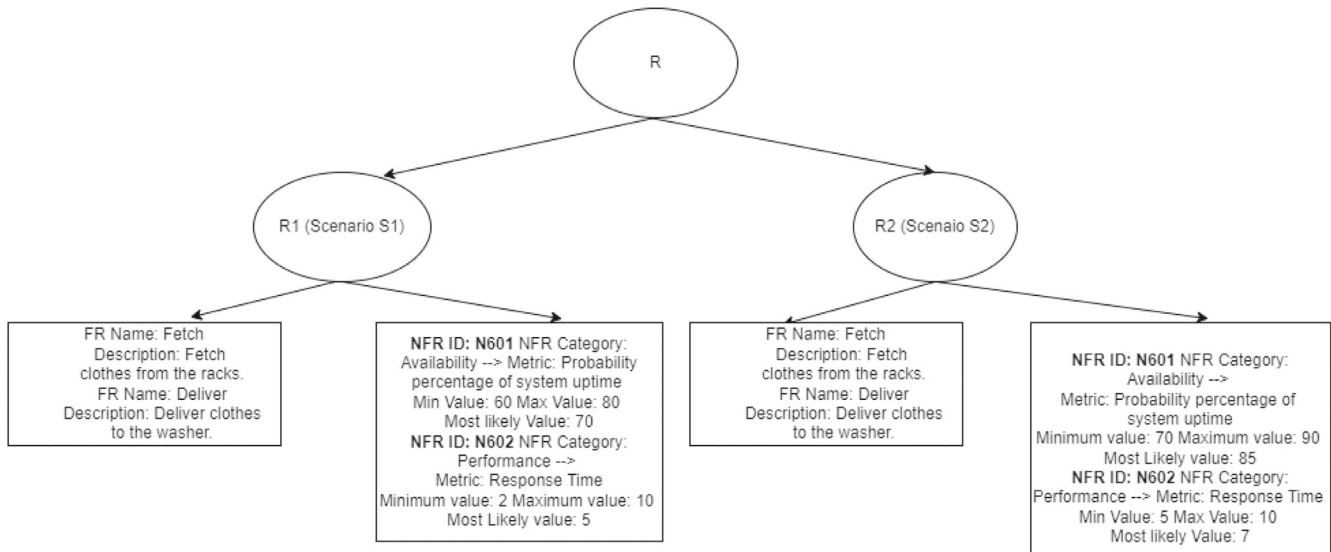


FIGURE 3 Scenario-specific requirement set.

TABLE 5 Example of QoS profile.

QoS profile	
Example 12	Policy List: Profile1
	QoS Profile Type: Location
	Reliability == BEST EffORT
	Durability == VOLATILE
	Deadline == 5
	Policy List: Profile2
	QoS Profile Type: Location
	Reliability == RELIABLE
	Durability == VOLATILE
	Deadline == 3

ports of the devices define the characteristic of communication. The *QoS Compatibility Check* module of the framework takes as input the system specification (in different scenarios), which includes the devices that are communicating among themselves to share information. The module generates incompatible QoS profiles for different communicating devices. The ROS2 community has already defined the set of QoS profiles that are incompatible. We have implemented those rules^h in the model checker in MPS. This *QoS Compatibility Check* module addresses the issue I-5 mentioned in Section 3.2.

Let us consider two QoS profiles *profile1* and *profile2* shown in Example 12 in Table 5 that are associated with ports OT102 and IN105 respectively (refer to Example 5 in Table 3). The port OT102 is publishing location information that is subscribed by port IN105. In Figure 4, we can see that the QoS profiles associated with these two ports are incompatible due to their *Reliability* and *Deadline* policy.

NFR consistency check

An autonomous system is built from an aggregation of several atomic and composite components. These heterogeneous components coordinate among themselves to achieve particular tasks.

Consider the situation where a robot is expected to deliver some goods in the hospital from point A to point B and the expected response time for the task is t_r sec. Now in performing this task the sensing device of the robot (response time t_s sec) will locate the goods, the task and motion planning software modules (response time t_m sec) compute a route for

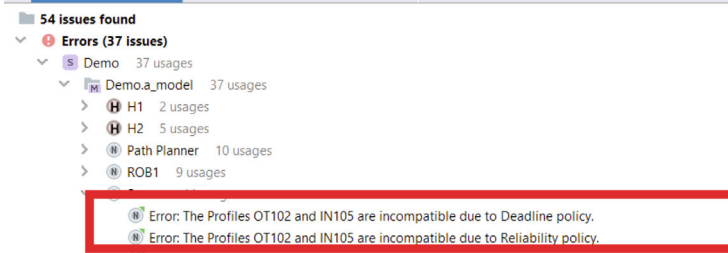


FIGURE 4 QoS profile compatibility check result.

Algorithm 1. NFR consistency check

Arguments:

1. C_{comp} : A set of composite components.

Output:

1. A set of higher-level NFRs incompatible with lower-level associated NFRs.

```

1: function NFR CONSISTENCY CHECK( $C_{comp}$ )
2:   for each  $comp \in C_{comp}$  do
3:     for each  $nfr \in comp$  do
4:        $cvalue \leftarrow$  COMPUTE( $nfr.parameters, nfr.operation$ )
5:        $result \leftarrow$  COMPARE( $cvalue, nfr.mostlikely$ )
6:       Print  $result$ .
7:     end for
8:   end for
9: end function

```

the robot and the wheels (time required to move from point A to B is t_w sec based on wheel velocity) help in the movement. Each of these components has its own individual response times. Hence it is necessary to compare whether these individual response times (t_s, t_m, t_w) of the components are sufficient to obtain the response time required for the task (t_r).

In our DSL metamodel, we have the provision for specifying NFRs for each individual component, and how the NFRs of different components are related. Algorithm 1 checks whether NFRs associated with high-level composite components are consistent with the non-functional properties of its constituting components. This consistency check is performed at the inter-component level that is among different components (both atomic and composite). The COMPUTE function applies the specified operation on the *most likely* values of the NFRs in the parameters field and stores it in variable *cvalue*. The function COMPARE compares the *cvalue* with the most likely value of the NFR in concern. This comparison also depends on the NFR category (refer to Section 3.1).

We have implemented an NFR category check before comparing their values. This consistency check method is executed for different requirement sets that exist for different scenarios. This *NFR Consistency Check* module addresses the issue I-2 mentioned in Section 3.2

In Example 7 in Table 4 we observed that NFR N601 is related to NFRs N101 and N301 and the Operation is Max. NFRs N101 and N301 are associated with the sub-components of the *ROBOT1* (*H1* and *H103* respectively). In this case, the maximum of their *most likely* values are not consistent with the *most likely* value of NFR N601. This is analyzed by the model checker in MPS and shown as an error in Figure 5.

NFR conflict check

NFR conflict check is performed at the intra-component level and it is the most important function of *Requirement Analysis*. The *NFR Conflict Check* module addresses the issue I-1 mentioned in Section 3.2. This module consists of two major activities: (1) Conflict Identification and (2) Conflict Impact Analysis.

Conflict identification: The *Conflict Identification* procedure is performed on the NFRs of each component (atomic and composite) defined in the specification. As mentioned earlier in Section 4.2.1 for each n scenarios in which

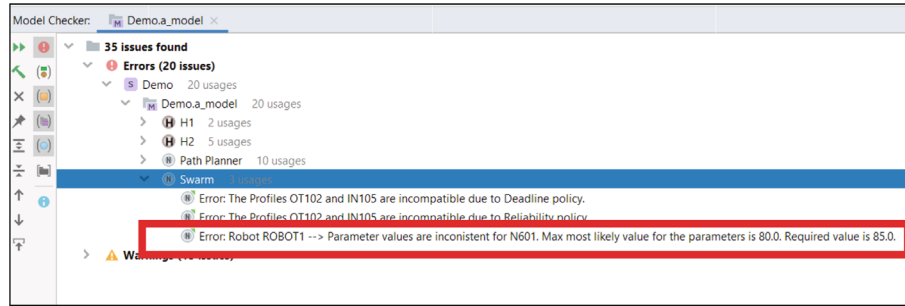


FIGURE 5 NFR inconsistency result.

Algorithm 2. NFR conflict identification

Arguments:

1. $Spec[n]$: An array of requirement specifications for n scenarios.
2. k : Let k be the total number of components in the specification.

Output:

1. $Conflict_i[k][col_{size}]$, $i \in [1, n]$: A set of 2-D arrays storing the conflicts for each component in n scenarios. The col_{size} is set to $\binom{m}{2}$, where m is the maximum total number of NFRs of all components.

```

1: function CONFLICT IDENTIFICATION( $Spec, k$ )
2:   Set  $index \leftarrow 1$ 
3:   while  $index \leq n$  do
4:     Fetch Specification  $Spec[index]$ .
5:     Set  $count \leftarrow 1$ 
6:     while  $count \leq k$  do
7:       Fetch specification for component  $conf_{count}$  in  $Spec[index]$ 
8:       Set  $conf_{count} \leftarrow 0$ .
9:       for each  $\langle nfr_i, nfr_j \rangle \in conf_{count}$  do
10:         $result \leftarrow CHECK(nfr_i, nfr_j)$ 
11:        if  $result = 1$  then
12:          Increment  $conf_{count}$ .
13:          Add  $\langle nfr_i, nfr_j \rangle$  to  $Conflict_{index}[count][conf_{count}]$ 
14:        end if
15:      end for
16:      Increment  $count$ .
17:    end while
18:    Increment  $index$ .
19:  end while
20: end function

```

the system is likely to operate the framework creates a different specification. Hence conflict identification is performed for each component in n scenarios. A pre-defined conflict catalog is used for detecting conflicts among NFRs (refer to note^{ll}). Algorithm 2 illustrates the steps for conflict identification. It takes a set of n requirement specifications as input. Then for each specification, it checks for the NFR conflicts in each of the components separately. The CHECK function checks whether a pair of NFRs are in conflict by referring to the conflict catalog and returns 1 or 0 respectively.

Conflict impact analysis: The objective of this activity is to analyze the risk (or severity) associated with different conflicting pairs of NFRs and how a change in the weight of one NFR impacts its conflicting NFR. It involves the following steps-

1. *Expected value computation*: We have used PERT⁴² for computing an initial expected value of each NFR. Each NFR is associated with three values- minimum value, maximum value and most likely value (refer to Section 4.1). The PERT determines the expected value using the following formula-

$$\text{Expected}_{value} = \frac{O_{val} + P_{val} + 4M_{val}}{6} \quad (1)$$

where, O_{val} refers to the optimistic value, P_{val} refers to the pessimistic value and M_{val} refers to the most likely value.

In the case of NFR of the category *C-1* (refer to Section 3.1) optimistic value is the minimum value and the pessimistic value is the maximum value. Similarly, for NFRs of category *C-2* (refer to Section 3.1) optimistic value is the maximum value and the pessimistic value is the minimum value. The expected values are computed for each NFR pair that is in conflict. The same NFR can have different expected values in different scenarios.

2. *Normalization of values*: The metrics of different NFRs have their minimum and maximum values in different ranges. The initial computed expected values of different NFRs lie in different ranges. These initial expected values are normalized in the range [0–1] using the following formula-

$$X_{normalizedval} = \frac{X - X_{min}}{X_{max} - X_{min}} \quad (2)$$

where X is any value that has to be normalized, X_{min} is the minimum value X can have and X_{max} is the maximum value X can have.

C-1 category NFRs are optimistic towards minimum value and *C-2* category NFRs are optimistic towards maximum value. To make the computation simpler we complement the normalized expected values of *C-1* category NFRs (refer to Equation 3).

$$X_{complement} = 1 - X_{normalizedval} \quad (3)$$

This step makes all NFRs optimistic toward maximum value. This normalization and complementation help in comparing the NFRs on a uniform manner.

Let us consider the NFR N602 in Example 7 in Table 4, that belongs to category *C-1*. Using PERT (Equation 1) the expected value is 5.33. The normalized value for N602 is 0.41625. Now complementing the normalized value using Equation (3) we get the value 0.58. It is to be noted that here we have not considered the impact of the scenario on the NFR N602.

3. *Estimating risk of conflict*: For every pair of NFR conflicts we classify them into one of the three following classes. This classification of conflict is done for each of the n requirement specifications. Suppose the NFR pair $\langle nfr_i, nfr_k \rangle$ in scenario m are in conflict with normalized (and maybe complemented) expected values E_i and E_k respectively. The expected values computed reflect the desired user expectation from the system. We consider these expected values and conflict information to determine the risk imposed by the NFR conflicts. If the computed expected values lie between 0 and 0.5 then it is assumed to be in the pessimistic range and that between 0.5 and 1 is to be in the optimistic range.
 - a. *Low risk*: If the values of E_i and E_k lies in the range [0.5, 1] then the NFR pair $\langle nfr_i, nfr_k \rangle$ are said to be at low-risk conflict. Now increasing the expected value of nfr_i will negatively influence (decrease) the value of nfr_k as they are in conflict. However, since the value of nfr_k is in the optimistic range the impact may not be too severe.
 - b. *Moderate risk*: The NFR pair $\langle nfr_i, nfr_k \rangle$ are said to be at moderate-risk conflict when one NFR have their expected value in the pessimistic range and another in the optimistic range. nfr_i negatively influences nfr_k . Suppose E_i lies in the range [0.5, 1] but E_k lies in the range [0, 0.5]. Now increasing the expected value of nfr_i will negatively influence (decrease) the value of nfr_k . If the value of nfr_k goes below a minimum threshold, it implies that the NFR cannot be satisfied.
 - c. *High risk*: If the values of E_i and E_k lie in the range [0, 0.5] then the NFR pair $\langle nfr_i, nfr_k \rangle$ are said to be at high-risk conflict. Since both lie in the pessimistic range whenever we try to improve the value of one NFR towards the optimistic range, it severely affects the other.

In Figure 6, the blue bar represents the initial expected value of E_k and green bar represents the initial expected value of E_i for low-risk, moderate risk and high-risk case respectively. Δ represents any constant value by which expected value of nfr_i is increased. Then expected value of nfr_k decreases by a value that is a function of $\Delta - (f(\Delta))$. The $f(\Delta)$ depends on the risk category and it is discussed in the next step.

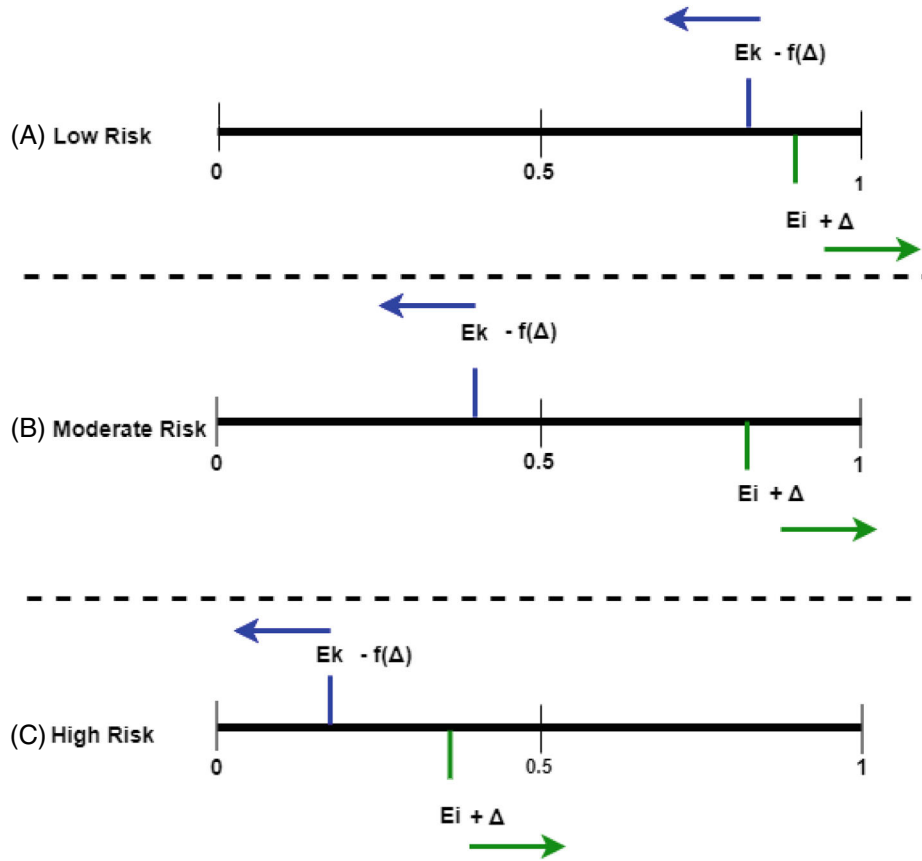


FIGURE 6 Risk associated with NFR conflicts.

4. *Impact analysis*: We have defined an *Affection function* that is a mathematical function for analyzing the risk profiles of different NFR conflicts and determining how a change in the expected value of one NFR negatively impacts the weight of another NFR. The impact value is computed based on the risk category as follows:
 - a. When the NFR pair $\langle nfr_i, nfr_k \rangle$ have low risk, increasing the value of NFR nfr_i will have a linear impact on the value of nfr_k and vice-versa. That is we increase the value of nfr_i by a constant Δ then the value of nfr_k decreases by $\Delta * diff$, where, $diff = E_k - 0.5$.
 - b. When the NFR pair $\langle nfr_i, nfr_k \rangle$ have moderate risk, increasing the value of NFR nfr_i , decreases the value of nfr_k polynomially and vice-versa. That is we increase the value of nfr_i by Δ then value of nfr_k decreases by Δ^{k*diff} , where k is any constant of power of 10. The value of $diff$ is determined using the same formula as above. The value of Δ and $diff$ both lies in the range $[0, 1]$. Δ to the power of $diff$ will give a very small value. Hence, we are multiplying $diff$ with k .
 - c. When the NFR pair $\langle nfr_i, nfr_k \rangle$ have high risk, increasing the value of NFR nfr_i , decreases the value of nfr_k exponentially and vice-versa. That is we increase the value of nfr_i by Δ then value of nfr_k decreases by $e^{\Delta*diff}$. The value of $diff$ is determined using the same formula as above.

The value of Δ lies in the range of $[0.1, 1 - E_i]$. We assume the minimum value of Δ to be 0.1 and the maximum value as $1 - E_i$, as the value of NFRs lies in $[0, 1]$ range.

Hence, the *Affection function* is defined as follows:

$$f(\delta) = \begin{cases} \Delta * diff & \text{if risk is low} \\ \Delta^{k*diff} & \text{if risk is moderate} \\ e^{\Delta*diff} & \text{if risk is high} \end{cases}$$

Algorithm 3 demonstrates the above-mentioned steps of conflict impact analysis activity.

Let us consider the NFRs $N601$ and $N602$ (refer to Example 7 in Table 4). Their initial expected values are found to be 0.59 and 0.61 respectively in scenario $S2$ (refer to Example 11 in Table 4). When trying to improve the value of $N601$, the value of $N602$ degrades linearly as they have low risks. If we increase the value of $N601$ by Δ then the value of $N602$ decreases by $\Delta * diff$. The value of Δ will lie in the range of 0.1 to $1 - 0.59$ that is, 0.41 and $diff$ value is $abs(0.5 - 0.61)$ that is, 0.11.

All these algorithms have been implemented within the model checker in MPS.

4.2.3 | NFR OPTIMIZATION

In this module, we apply a multi-objective optimization approach to compute the optimal satisfaction values of NFRs in different scenarios for the various components in a robotic system. This optimization module provides feasible satisfiability values of each NFR given their conflicts and association with various FRs. Based on the output of the optimization module, system designers can build appropriate configurations of the system in different scenarios. This reduces the cost and risk of system refactoring.

We have used the *pymoo* library in python to solve our optimization problem. Each component has one or more functional goals that it must perform. These functional goals have different degrees of association with one or more NFRs (refer to Example 8 in Table 4). These NFRs may also have a negative impact on each other. The *AFFECTION* function (refer to Algorithm 3) provides the degree of conflict among different pairs of NFRs. Considering the FR-NFR dependency and NFR conflict relationship we create a multi-objective optimization problem for each component considering their NFR values in different scenarios. If the system has to operate in n scenarios, then each component will have a different optimization problem for n scenarios.

Let us again consider the NFR pair $N601$ and $N602$. The robot *ROBOT1* (refer to Example 1 in Table 2) has two functional goals *Fetch* and *Deliver*. The goal *Fetch* is also associated with NFRs $N601$ and $N602$ with dependency values 8 and 6 respectively. The goal *Deliver* is associated with NFRs $N601$ and $N602$ having dependency values 8 and 9 respectively. Let $w1$ and $w2$ be the decision variables for NFRs $N601$ and $N602$ respectively. The objective functions are formed by multiplying the decision variables $w1$ and $w2$ with the dependency values corresponding to each FR. Two objective functions will be created with respect to each functional goal (*Fetch* and *Deliver*). The constraints are formed by the conflict impact relationship derived by Algorithm 3. The constraints show how an increase in the weight of one NFR affects another NFR. In this case, we know that if we increase the value of $N601$ by Δ then the value of $N602$ decreases by $\Delta * diff$. The optimization problem is as follows:

$$\begin{aligned} & \underset{w1, w2}{\text{maximize}} \begin{cases} 8w1 + 6w2 \\ 8w1 + 9w2 \end{cases} \\ & \text{s.t. } w1 + w2 + \delta - \delta * diff \geq 0, \\ & \quad w1 + w2 + \delta - \delta * diff \leq 2, \\ & \quad diff = 0.11, \delta = 0.1 \dots, 0.41 \end{aligned}$$

The values of $diff$ and Δ are explained in the previous section.

By solving this optimization problem using NSGA 2 algorithm with a population size 100 and number of generations 50, we obtain the weights of $w1$ and $w2$, respectively. These weights may vary in different scenarios. Based on these weights system designer can know apriori the optimal satisfaction values of the concerned NFRs in different scenarios. This aids in the explainability of the system behavior.

5 | EXPERIMENTAL EVALUATION

In this section, we demonstrate the experiments performed to validate the proposed *SCARS* framework. The proposed approach can be validated on any autonomous system. In this work, we have used a simple ROS-based robotic system to perform the validation. Through these experiments, we show how the optimal values produced by the framework can be used in real scenarios. The experiments are executed on a workstation with AMD Ryzen 9 processor, GPU AMD Radeon

Algorithm 3. NFR conflict impact analysis**Arguments:**

1. $Conflict_i[k][col_{size}]$, $i \in [1, n]$: A set of n number of 2-D arrays storing the conflicts generated by Algorithm 2.

Output:

1. $Risk_i[k][col_{size}]$, $i \in [1, n]$: An array storing risk of each NFR conflict.
2. $Impact_i[k][col_{size}]$, $i \in [1, n]$: An array storing impact of each NFR conflict.

```

1: function AFFECTION(Conflict1[k][colsize],.....Conflictn[k][colsize])
2:   for spec = 1 to n do
3:     for row = 1 to k do
4:       for col = 1 to colsize do
5:         if Conflictspec[row][col] ≠ ∅ then
6:           Fetch NFR pair ⟨ nfri, nfrk ⟩ from Conflictspec[row][col]
7:           Ei ← EXPECTEDVALUE(nfri)
8:           Ek ← EXPECTEDVALUE(nfrk)
9:           Let Δ be any value between [0.1, (1-Ei)].
10:          Let diff ← abs(0.5 - Ek).
11:          if 0.5 < Ei, Ek ≤ 1 then
12:            Riskspec[row][col] ← "Low-Linear"
13:            Impactspec[row][col] ← Δ*diff
14:          else if 0.5 < Ei ≤ 1 and 0 ≤ Ek ≤ 0.5 then
15:            Riskspec[row][col] ← "Moderate-Polynomial"
16:            Impactspec[row][col] ← Δk*diff, ▷ where k = 10random(1,10)
17:          else if 0 ≤ Ei, Ek ≤ 0.5 then
18:            Riskspec[row][col] ← "High-Exponential"
19:            Impactspec[row][col] ← eΔ*diff
20:          end if
21:        end if
22:      end for
23:    end for
24:  end for
25: end function

```

RX, 32GB DDR5 RAM and Ubuntu 20.04 operating system. The experimental scripts and results are available at our github repository.^{††} The experimental steps are as follows:

Step 1: Selection of a simulator

We have selected the ROS 2 Gazebo simulation stack for the iRobot® Create® 3 Educational Robot for performing our experiments. iRobot® Create® 3 Simulator can be used to quickly develop new applications and eventually run them on a real robot without having to change anything. We have used two different environments in the Gazebo simulation for conducting the experiments. Figure 7A,B are the two simulation environments. Figure 7A shows a home environment consisting of two rooms and a single robot. Figure 7B shows a hospital environment with multiple rooms and a single robot.

Step 2: Defining the functional goals

The Create® 3 robot can be navigated to a specified odometry position and orientation. In our experiments, we used middleware APIs for navigating the robot to different positions. We define a simple functional task for the robot:

^{††}<https://github.com/RESSA-ROB/SCARS/tree/main/Experiments>.



(A) Home Environment



(B) Hospital Environment

FIGURE 7 Simulation environments. (A) Home environment, (B) hospital environment.

1. $T-1$: Robot begins at an initial position **A**, picks up an object from position **B** and delivers it as position **C**.

The Create[®] 3 robot design does not provide the provision for the actual picking up of an object from a place. Thus, in our experiments, we simply move the robot to a location **B** and introduce a latency time for object picking. The position **A**, **B** and **C** were determined randomly. The same task is executed by the robot in both simulation environments (refer to Figure 7A,B)

Step 3: Determining the NFRs associated with the functional goals

The non-functional parameters that can be manipulated within this simulator are: (i) safety and (ii) speed. The non-functional parameters like response time and battery discharge can be observed from the logs generated by the simulator. The NFRs that need to be satisfied for task $T-1$ are as follows-

1. $N-1$ response time: The response time associated with task $T-1$ is a category $C-1$ NFR.
2. $N-2$ battery state or battery discharge rate: The battery state of the robot is also category $C-1$ NFR.
3. $N-3$ speed: The speed of the robot is a category $C-2$ NFR.
4. $N-4$ safety: The safety of the robot is a category $C-2$ NFR.

These qualitative definitions of NFRs have been quantified while creating the DSL specification within the SCARS framework.

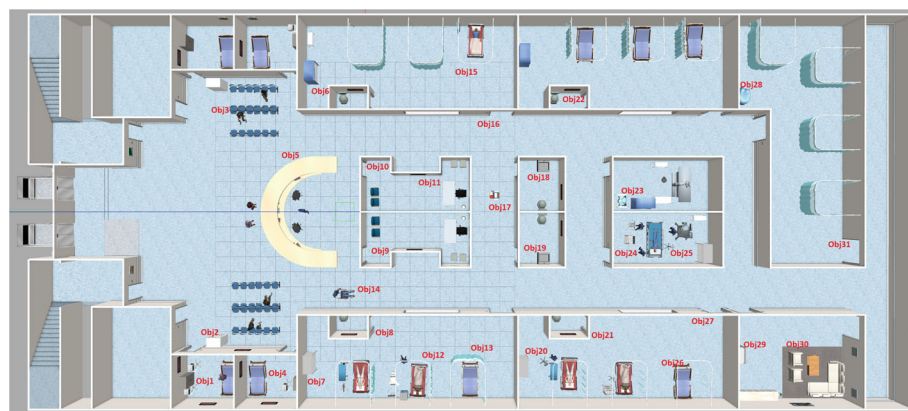
Step 4: Determining the scenarios that may occur for task T-1

We have instantiated the task $T-1$ for 100 different settings in both environments. Thus we have 100 settings for the home environment (Figure 7A) and 100 settings for the hospital environment (Figure 7B). In each of these settings the positions **A**, **B** and **C** (defined in *Step-2*) are unique. The positions **A**, **B** and **C** are randomly generated within the room and hospital map and the details are discussed in the Annexure section. In Figure 8A, the objects marked in red as $Ob1-Ob22$ in the home are the obstacles that the robot has encountered in its path while executing the task $T-1$. Similarly, in Figure 8B the objects marked in red as $Ob1-Ob31$ in the hospital are the obstacles that the robot has encountered in its path while executing the task $T-1$. The positions of the obstacles are fixed within the room and hospital map. Now for performing task $T-1$ by the robot along the path **A-B-C** in these 100 different settings (in both environments) different situations can arise as follows:

1. The path **A-B-C** does not include obstacle.
2. The path **A-B-C** has only one obstacle.
3. The path **A-B-C** has multiple obstacles.



(A) Home Environment



(B) Hospital Environment

FIGURE 8 Simulation environments with obstacles.

TABLE 6 Experimental scenario.

Scenario	Contexts		
	# Obstacle	Obstacle before pickup	Obstacle after pickup
S1	0	0	0
S2	1	1	0
S3	1	0	1
S4	2	2	0
S5	2	0	2
S6	2	1	1
S7	3	1	2

TABLE 7 NFR parameter values.

NFR	Minimum value	Maximum value	Most likely value
Battery discharge (energy efficiency)	Battery discharged for moving the robot at two extreme points at maximum speed	Battery discharged for moving the robot at two extreme points at minimum speed	Based on NFR category C-1
Response time (Performance)	Time taken for moving the robot at two extreme points at minimum speed	Time taken for moving the robot at two extreme points at minimum speed	Based on NFR category C-1
Speed	Create [®] 3 robot documentation	Create [®] 3 robot documentation	Based on NFR category C-2

These different situations form different scenarios. Table 6 illustrates the different scenarios that we have obtained based on the obstacles in the home and hospital environment and randomly generated positions for **A**, **B** and **C** for both environments. In the home environment (Figure 7A) we have encountered all seven scenarios in Table 6. In the hospital environment (Figure 7B) we have encountered only the first six scenarios.

Step 5: Creating DSL specification

In this step, we elaborate on the DSL specification created for this experiment. DSL specification in this case includes the following-

- Component specification:** In our experiments, only a single robot exists. Create[®]3 robot consists of different hardware (like mechanical and electrical) and software (sensing and navigation) parts. Figure B1 shows a portion of the component specification created for the Create[®]3 robot.
- Functional goal specification:** The task *T-1* defined in Step 2 is captured within the DSL specification in Figure B2. In the DSL specification, we have divided the task *T-1* into two parts that are: (i) picking up an object that involves moving from point **A** to **B** (*RG101*) (ii) delivering the object from point **B** to **C** (*RG102*). This is because in Table 6 we can observe that robot may collide with an obstacle either before picking up an object or after picking up an object. Hence the NFR parameter values (like speed) of the robot differ before and after picking up an object in different scenarios. The functional goal specification in both environments is the same since the same task is executed.
- NFR specification:** Figure B3A,B shows the NFRs specified corresponding to FRs *RG101* and *RG102*. The FRs can have the same NFR metric values or different ones. Figure B3C shows the corresponding FR-NFR dependencies. We have defined three NFR parameters in the DSL specification—Speed, Response Time and Energy efficiency (for Battery State). We have not captured the safety parameter in the DSL specification as in the simulator it takes only fixed qualitative values (none, back_up_only, full). The SCARS framework only supports quantitative metric values of NFRs. The specification in Figure B3A–C are for the home environment. The specification for the hospital environment is different as the NFR priorities vary in different environments. Table 7 illustrates how the maximum, minimum and most likely values of NFRs are set within the DSL specification.
- Scenario specification:** Figure B4 shows the different contexts and how these contexts can be combined to create scenarios in Table 6. Here we have only shown for scenario *S3* in home environment. In Context-NFR Association

TABLE 8 Parameters of optimization problem.

Parameters	Value
Number of variables	6
Number of objectives	2
Number of constraints	8
Method	NSGA-2
Population size	100
Number of generations	50

section in Figure B4, it can be observed that with each context we associate different NFRs that might get affected. In Scenario-NFR Impact section we define how the values of NFRs *N105*, *N106* and *N107* are affected based on the scenario. These values are determined considering robot safety (To ensure the robot's safety against damages, the speed has to be lowered as it reduces the impact of the collision with the obstacle) and the priority of different NFRs. We are not manipulating the values of NFRs *N101*, *N102* and *N103* as they are associated with *RG101* and here obstacle is encountered while achieving *RG102*. Hence in the scenario-specific requirements specification generated by MPS for scenario *S3* the values of NFRs *N101*, *N102* and *N103* will remain the same as in Figure B3A, but the values of NFRs *N105*, *N106* and *N107* will be replaced with the one in Figure B4. The other scenario specifications are available within the language model at.^{‡‡}

Step 6: Generating optimal values of NFRs

The model checker in MPS identifies the conflicts (refer to Figure B5) among NFRs in the specification. It then uses this conflict information and FR-NFR dependencies (refer to Figure B3C) to generate a multi-objective optimization problem. There are a total of seven different optimization problems generated for each of the seven scenarios in Table 6 for the home environment. In the case of the hospital environment, six different optimization problems were generated for the first six scenarios in Table 6. Figure B6 shows the multiobjective optimization problem created for the requirement specification of scenario *S3* in the home environment. This multi-objective optimization problem is solved using the Pymoo library in python. We have used the NSGA-2 algorithm for solving this optimization problem. NSGA-2 algorithm is proven to be computationally efficient for two objective optimization problems.⁴³ Table 8 shows the parameters set for solving the optimization problem. The population size and the number of generations are subject to vary depending upon the problem size. Each constraint in Figure B6 is transformed into two constraints one satisfying the lower bound and another the upper bound. Hence the total number of constraints in Table 8 is 8. The decision variables w_{s1} and w_{s2} is for speed values for FRs *RG101* and *RG102* respectively. The decision variables w_{B1} and w_{B2} is for battery discharge values for FRs *RG101* and *RG102* respectively. The decision variables w_{R1} and w_{R2} is for response time values for FRs *RG101* and *RG102* respectively. The values of variables $[w_{s1}, w_{B1}, w_{R1}, w_{s2}, w_{B2}, w_{R2}]$ are found to be $[0.83, 0.71, 0.75, 0.76, 0.75, 0.8]$. These values imply the maximum values each of the NFRs can have in that particular scenario (*S3*). The multi-objective optimization problems for other scenarios can be visualized by running the language model available at[†].

Step 7: Setting the NFR parameter values within the simulator

The values obtained in the previous step are normalized in the 0 – 1 scale and have to be mapped to their respective ranges. As mentioned earlier, the simulator takes as input speed values and generates response time and battery discharge values as output. So for goal *RG101* the value of the speed metric is 0.45 and for goal *RG102* the value of the speed metric is 0.3. These values are obtained by mapping the optimal speed values (value of w_{s1} and w_{s2}) in their respective ranges using the formula (4). The value of w_{s1} is mapped in the range of NFR *N101* in Figure B3A. The value of w_{s2} is mapped in the range of NFR *N105* in Figure B1, B4. After setting the values the simulator is executed to record run-time NFR values.

^{‡‡}https://github.com/RESSA-ROB/SCARS/blob/main/DSL_v1.zip.

TABLE 9 Experimental results for home.

Scenario	Number of cases	Velocity for FR RG101	Velocity for FR RG102	Average response time	Average battery discharge
S1	42	0.46	0.46	48.12	0.59
S2	14	0.4	0.46	76.60613571	0.7535714286
S3	33	0.45	0.3	81.53432424	0.7615151515
S4	10	0.33	0.46	109.65545	0.895
S5		0.46	0.24	122.73635	0.87
S6		0.4	0.3	91.33313333	0.7666666667
S7		0.4	0.24	153.1283667	0.9733333333

TABLE 10 Experimental results for hospital.

Scenario	Number of cases	Velocity for FR RG101	Velocity for FR RG102	Average response time	Average battery discharge
S1	52	0.46	0.46	160.2063904	1.430192308
S2	23	0.44	0.46	175.3486217	1.558695652
S3	17	0.46	0.32	192.9473765	1.462941176
S4	8	0.4	0.46	138.9066	1.15
S5		0.4	0.313	212.534925	1.34
S6		0.4	0.32	182.617	1.685

$$Val_{new} = ((Val_{old} - old_{min}) * new_{range}) / old_{range} \quad (4)$$

where, $old_{range} = old_{max} - old_{min}$ and $new_{range} = new_{max} - new_{min}$.

The code for running the different scenarios within the simulator is made available at⁴.

Step 8: Obtaining the NFR values from the simulator

This is the final step of the experiment. We record the response time and battery discharge values for the different scenarios. Table 9 provides a summary of the NFR parameter values recorded in different scenarios for the home environment. Similarly, Table 10 provides a summary of the NFR parameter values recorded in different scenarios for the hospital environment. Tables 9 and 10 record the number of times each scenario has occurred in the 100 different settings. The velocity or speed metric value for FR RG101 and RG102 is determined by Step 5–7 for each scenario independently. Tables 9 and 10 also record the average response time and battery discharge in each scenario. The distribution of the number of times each scenario occurred depends on the random coordinates generated for executing task $T-1$ in the two environments.

5.1 | Discussion

5.1.1 | Analysis of results

The experimental Step 6 generates the optimal values of different NFR parameters (speed, response time and battery discharge). The optimal speed values are fed to the simulator for executing the tasks in different scenarios. The simulator generates the response time and battery discharge as log records. This generated response time and battery discharge are compared with the optimal values (of response time and battery discharge) generated by the optimization algorithm to validate. It is to be noted that we have run the result in the simulator in each setting three times and taken an average of them. Now, we analyze the NFR parameter values obtained from the simulator w.r.t each scenario.

TABLE 11 Optimal values for NFR parameters in S1.

NFR parameters	FR RG101		FR RG102	
	Home	Hospital	Home	Hospital
Speed	0.46	0.46	0.46	0.46
Response time	50 units	100 units	70 units	150 units
Battery discharge	0.4%	1%	0.6%	1.5%

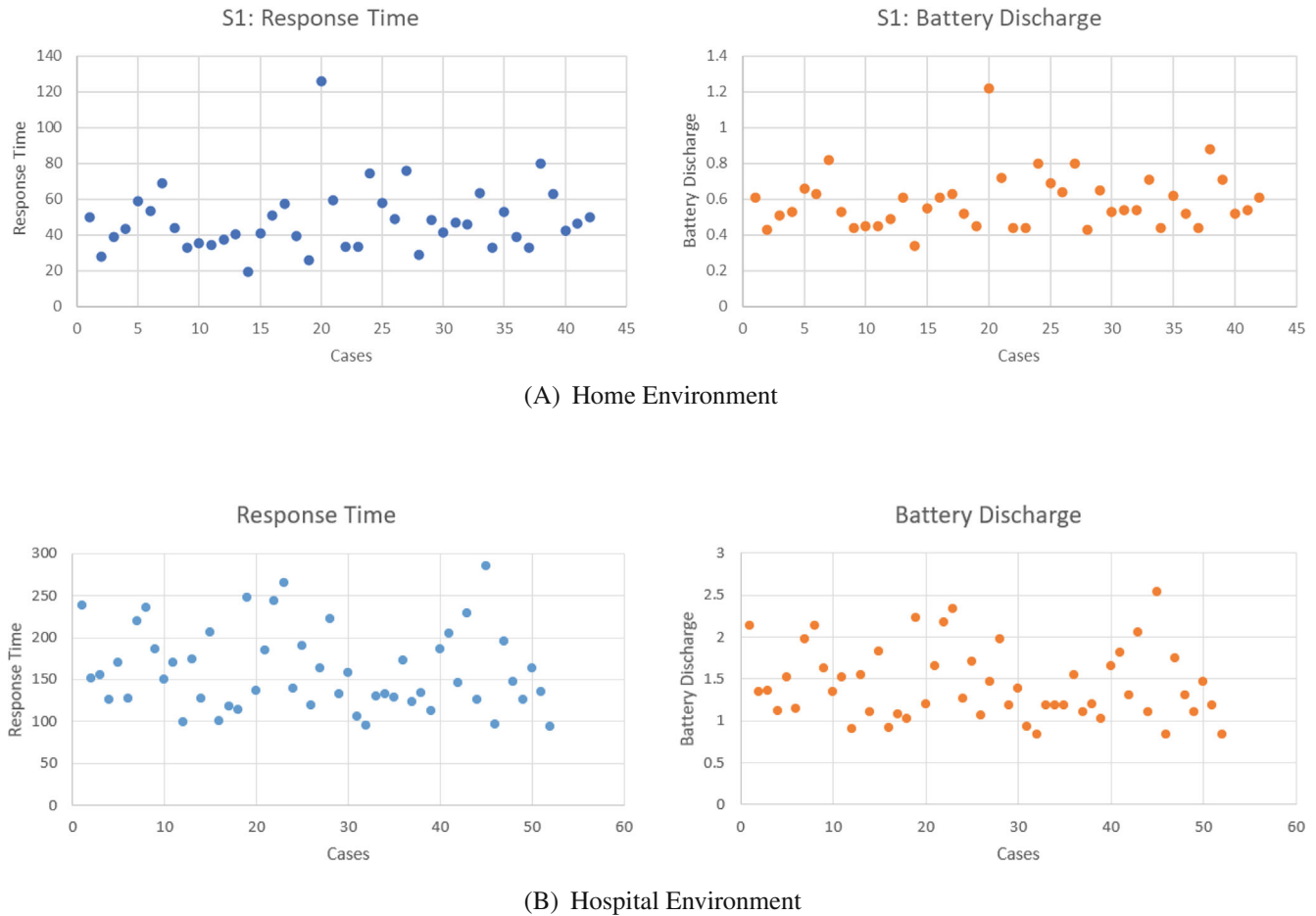


FIGURE 9 NFR parameter values in S1. (A) Home environment, (B) hospital environment.

- Scenario *S1*: In this scenario, the robot encounters no obstacles in its path. Table 11 shows the optimal values (maximal) of NFR parameters generated by the optimization algorithm for home and hospital environment. Figure 9A shows the distribution of total response time and total battery discharge in home for the 100 settings as obtained from the log records of the simulator. Figure 9B shows the distribution of total response time and total battery discharge in hospital for the 100 settings as obtained from the log records of the simulator. In both home and hospital environment we observe that the NFR parameter value from the simulator lies within the maximum optimal value (refer to Table 11) except for very few cases where a deviation is observed.
- Scenario *S2*: In this scenario, the robot encounters a single obstacle before picking up the object. Table 12 shows the optimal values (maximal) of NFR parameters generated by the optimization algorithm for home and hospital environment. Figure 10A shows the distribution of total response time and total battery discharge in home for the 100 settings as obtained from the log records of the simulator. Figure 10B shows the distribution of total response time and total battery discharge in hospital for the 100 settings as obtained from the log records of the simulator. In both home and hospital environment we observe that the NFR parameter value from the simulator lies within the optimal value (refer to Table 12) for all the cases.

TABLE 12 Optimal values for NFR parameters in S2.

NFR parameters	FR RG101		FR RG102	
	Home	Hospital	Home	Hospital
Speed	0.4	0.44	0.46	0.46
Response time	50 units	199.91 units	70 units	100 units
Battery discharge	0.5%	1.99%	0.6%	1.0%

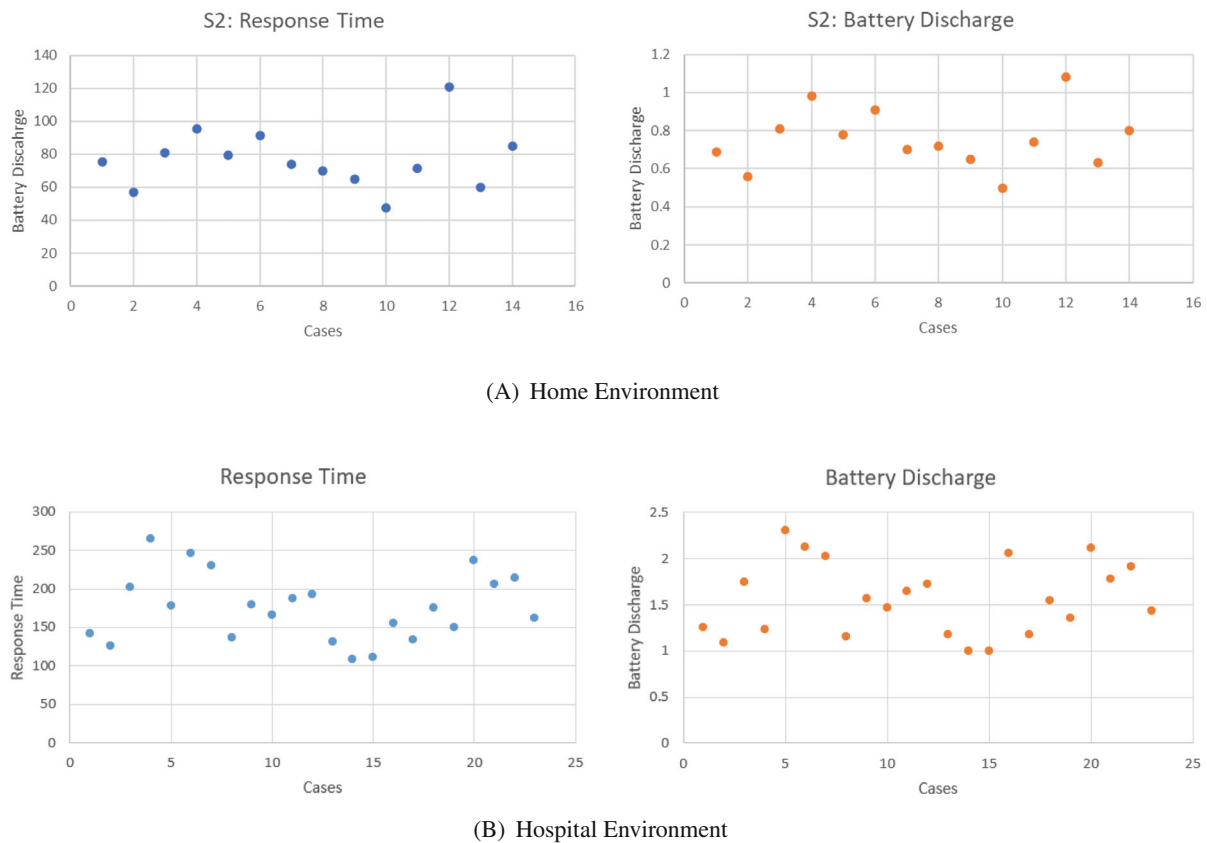
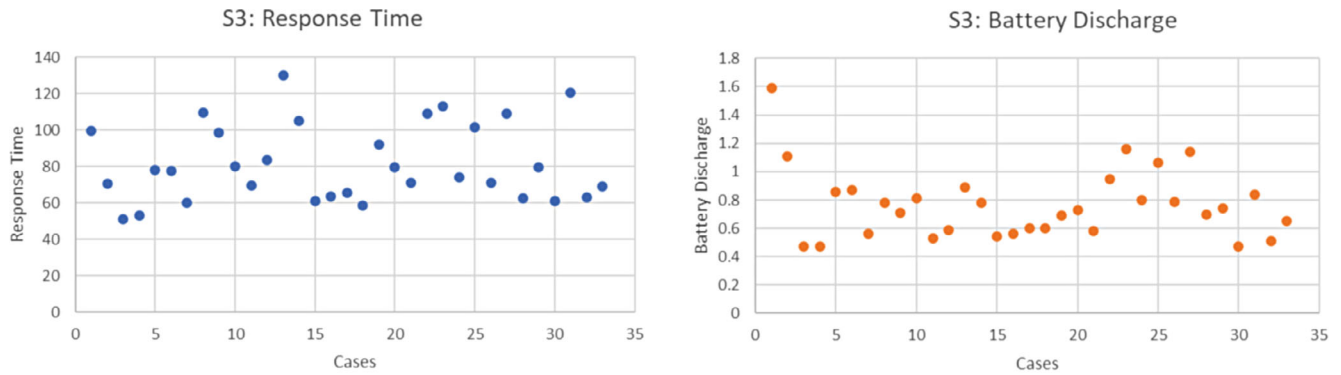


FIGURE 10 NFR parameter values in S2. (A) Home environment, (B) hospital environment.

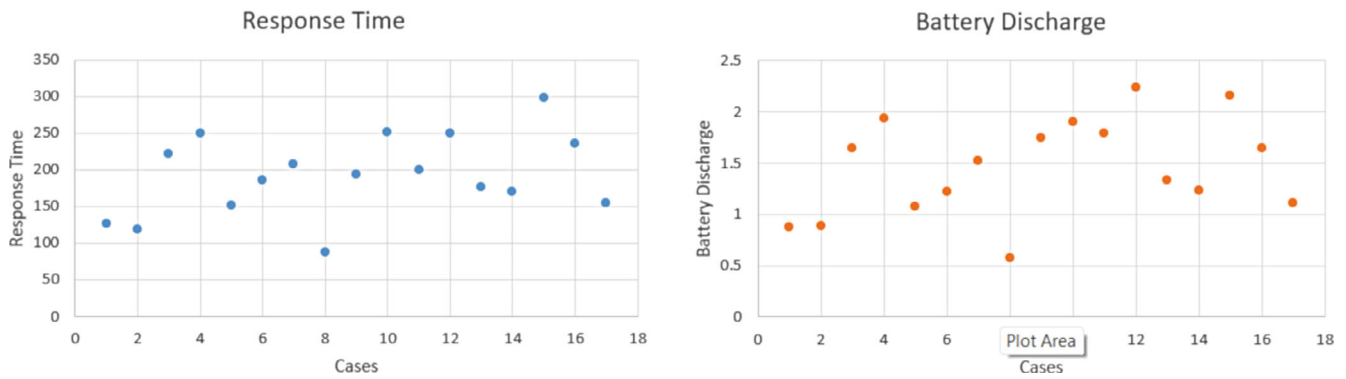
- Scenario S3: In this scenario, the robot encounters a single obstacle after picking up the object. Table 13 shows the optimal values (maximal) of NFR parameters generated by the optimization algorithm for home and hospital environment. Figure 11A shows the distribution of total response time and total battery discharge in home for the 100 settings as obtained from the log records of the simulator. Figure 11B shows the distribution of total response time and total battery discharge in hospital for the 100 settings as obtained from the log records of the simulator. In both home and hospital environment we observe that the NFR parameter value from the simulator lies within the optimal value (refer to Table 13) for all the cases.
- Scenario S4: In this scenario, the robot encounters two obstacles before picking up the object. Table 14 shows the optimal values (maximal) of NFR parameters generated by the optimization algorithm for home and hospital environment. In home environment out of 100 settings this scenario occurred only twice and in hospital only once. In both home and hospital environment we observe that the NFR parameter value from the simulator lies within the optimal value (refer to Table 14) for the three cases.
- Scenario S5: In this scenario, the robot encounters two obstacles after picking up the object. Table 15 shows the optimal values (maximal) of NFR parameters generated by the optimization algorithm for home and hospital environments. In the home environment out of 100 settings, this scenario occurred only twice and in the hospital only thrice. In both home and hospital environments, we observe that the NFR parameter value from the simulator lies within the optimal value (refer to Table 13) for the five cases.

TABLE 13 Optimal values for NFR parameters in S3.

NFR parameters	FR RG101		FR RG102	
	Home	Hospital	Home	Hospital
Speed	0.45	0.46	0.3	0.32
Response time	50 units	100 units	80 units	249 units
Battery discharge	0.4%	1.0%	1.5%	1.99%



(A) Home Environment



(B) Hospital Environment

FIGURE 11 NFR parameter values in S3. (A) Home environment, (B) hospital environment.

TABLE 14 Optimal values for NFR parameters in S4.

NFR parameters	FR RG101		FR RG102	
	Home	Hospital	Home	Hospital
Speed	0.45	0.4	0.3	0.46
Response time	80 units	200 units	50 units	100 units
Battery discharge	1.2%	2.0%	0.4%	1.0%

TABLE 15 Optimal values for NFR parameters in S5.

NFR parameters	FR RG101		FR RG102	
	Home	Hospital	Home	Hospital
Speed	0.46	0.46	0.24	0.313
Response time	50 units	100 units	100 units	299.17 units
Battery discharge	0.4%	1.0%	1.5%	1.99%

TABLE 16 Optimal values for NFR parameters in S6.

NFR parameters	FR RG101		FR RG102	
	Home	Hospital	Home	Hospital
Speed	0.4	0.44	0.3	0.32
Response time	50 units	199.91 units	80 units	249 units
Battery discharge	0.5%	1.99%	1.5%	1.99%

- Scenario S6: In this scenario, the robot encounters two obstacles, one before picking up the object and another after picking up the object. Table 16 shows the optimal values (maximal) of NFR parameters generated by the optimization algorithm for home and hospital environment. In home environment out of 100 settings this scenario occurred only thrice and in hospital only four times. In both home and hospital environments, we observe that the NFR parameter value from the simulator lies within the optimal value (refer to Table 16) for the seven cases.
- Scenario S7: In this scenario, the robot encounters three obstacles, one before picking up the object and two after picking up the object. This scenario was observed only in the home environment based on the randomly generated coordinates for the task. The optimal values for speed or velocity are found to be 0.4 and 0.24 for FRs RG101 and RG102 respectively. The optimal response times are 50 and 100 units for FR RG101 and RG102 respectively. That is total response time should not be more than 150 units. The optimal values for battery discharge are 0.4 and 1.5 for FR for RG101 and RG102 respectively. That is total battery discharge should not be more than 1.9 unit. This scenario has occurred only in two settings. Here in one case, we observe the response time recorded from the simulator to be slightly more than the derived optimal value.

The total response time and battery discharge depends on the (i) speed (ii) distance covered (iii) number of obstacles encountered in its path. When the robot collides with an obstacle it stops, moves back and detours to reach the destination. This detouring requires some additional time and energy which may vary depending upon the size of the obstacle. This may account to the deviation of NFR values from the optimal values in some cases. In some cases, the distance may be very small and hence response time appear to be much lower than the maximum (optimal) value produced by our framework. Since the positions are randomly determined for task *T-1*. We have obtained only a small number of cases for scenarios S4–S7. In those small cases, only a single violation of optimal values is observed. However, from this, we cannot conclude the optimal values derived are perfect for those scenarios.

Through these experiments, we have tried to show how the derived optimal values can be used in building a smart system that can adapt to various scenarios. We found that the NFR parameter values derived for most of the cases were satisfied. The values of speed in different scenarios are obtained considering its conflict with other NFRs and different contexts occurring. The complete set of experimental results are provided at our github repository.

5.1.2 | Comparison with existing works

In Table 1, we have provided a summary of different DSL proposed for robotic systems. Most of these works have considered the specification of components, communication among components and FRs. Some of them allow the specification of NFRs also, but they have not done any analysis regarding their conflicts. We find only a single work that tried to correlate NFRs with context information. However, there are not enough research works that have tried to address the issues of NFRs and the impact of contexts on them. There are few works that have only analyzed temporal NFRs for robotic systems. The proposed SCARS framework is an integration of specification and analysis. It provides a specification

portion that tries to cover all aspects of a robotic system within a single DSL metamodel. The analysis portion checks for inconsistencies, incompatibilities and conflicts among the non-functional parameters. Additionally, it provides optimal satisfaction values of different NFRs that are in conflict.

5.1.3 | Limitations

The limitations of this experimental evaluation are as follows:

1. The experiments are performed considering static contexts only. There may be dynamic contexts as well (like people moving in the room). In such scenarios, it will be more challenging to adjust the NFR parameters accordingly. We have not considered this issue within the scope of this work.
2. The experiments are conducted considering only formal specification and context-NFR impact values are provided depending on the understanding of the system engineers. It will be interesting if machine learning-based methods are integrated to study environments and their impact on various non-functional parameters in the system.
3. The optimal values in the experiments are obtained using only one genetic algorithm. It is to be further evaluated against other genetic algorithms as a part of our future works.

6 | THREATS TO VALIDITY

1. The first issue is related to the specification of contexts or scenarios. The framework requires analysts or engineers to be aware of different contexts and scenarios in which the system is likely to operate. However, there may be always certain contextual parameters that remain unknown during the design of the system.
2. The second threat to validity is related to the specification of scenario-NFR impact values. These values are often dependent upon the understanding of the analyst. This may introduce ambiguity or inconsistency in the specification. This can be resolved by the use of machine-learning-based methods to study scenarios and their impact NFRs. In an earlier work,⁴⁴ attempts have been made to provide a framework that qualitatively derives the correlations between contexts and NFR conflicts. Such frameworks can be useful to predict scenario-NFR impact correlations rather than manually providing them.
3. Another issue concerns the optimal values produced, that depend upon the conflict relationship between NFRs and FR-NFR dependency (specified in the objective function). The FR-NFR dependency values can again be subjective depending upon the understanding of the analyst. Hence a change in these values can result in a variation of the optimal values.
4. The last threat to validity is related to the use of a simulator for experimental evaluation. A simulation environment may not be an exact representation of reality. Hence the validity of the results are still subjective. The evaluation needs to be performed in real settings or in other similar simulation platforms.

7 | CONCLUSION

In general, most of the existing formal method based approaches for resolving conflicts in the requirements are concerned with functional requirements only. In spite of being a major factor in deciding the user acceptance and eventual success of a system, the NFRs are often considered something that someone will eventually take care of. The proposed *SCARS* framework provides a requirement specification DSL and also analyzes the conflicts, inconsistencies, and incompatibilities among the NFRs. Further, it provides an optimization module to generate optimum satisfaction values of different NFRs in various contexts. We have experimentally evaluated our framework using Gazebo simulation and Create[®]3 robot. The experimental result shows that the predicted optimum value satisfies the robot's run-time behavior (non-functional). Thus, the *SCARS* framework can be deployed to analyze robotic system behavior before the actual deployment. The optimum NFR values can help the system designer in building appropriate software operationalizations and reduce the cost of changes.

The *SCARS* framework is limited to handling only static contexts. However, in real scenarios, many dynamic objects like humans exist in the environment in which the robot operates. As a part of future work, we aim to extend our framework to model and analyze dynamic contextual parameters.

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AUTHOR CONTRIBUTIONS

All authors equally contributed in this work and writing the manuscript.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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APPENDIX A. GENERATION OF CO-ORDINATE POINTS

First, the coordinates for the extremities of the simulation environment have to be determined. For the environments used in our experiments, the extremity X and Y coordinates were:

1. AWS small house: (−9, 9) and (−5.5, 5.5)
2. AWS hospital: (−12, 10) and (−32, 10)

Next, a script to generate the desired number of coordinates has to be created. For our experiments, we generated a set of three random coordinates per iteration, namely for the start, fetch, and deposit positions. These coordinates were generated using a Python script that leveraged *numpy.random.uniform* random sampling method. A map of the three coordinates is generated per iteration as a tuple of the coordinate list.

APPENDIX B. DSL SPECIFICATION FOR EXPERIMENTS

Figures B1,B2,B3,B4,B5, and B6 shows the DSL specifications optimization problem for our experiments.

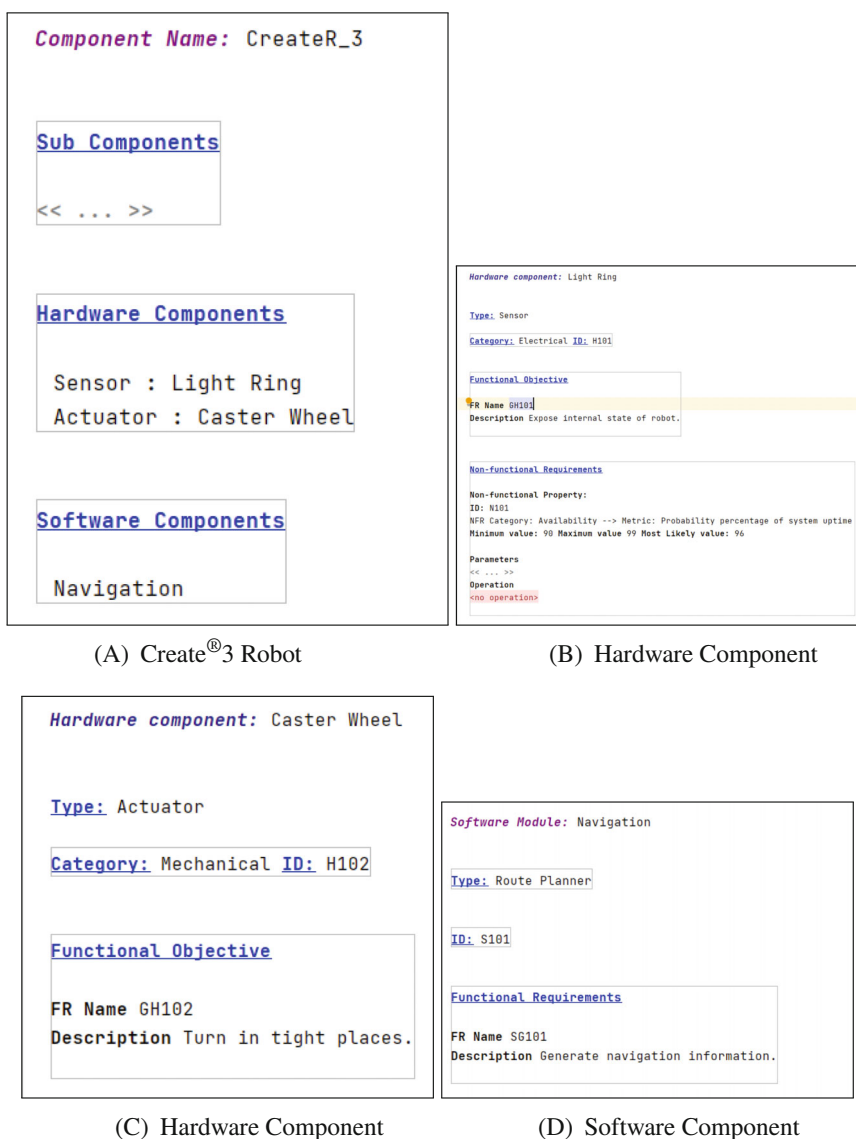


FIGURE B1 Component DSL. (A) Create[®]3 robot, (B) hardware component, (C) hardware component, (D) software component.

```

Functional Objective

FR Name RG101
Description Move from point A to B to pick up object.

FR Name RG102
Description Move from point B to C to deliver objects.

```

FIGURE B2 Functional goals DSL.

<pre> Non-Functional Objective Non-functional Property: ID: N101 NFR Category: Movement_Efficiency --> Metric: Speed Minimum value: 0.1 Maximum value 0.46 Most Likely value: 0.4 Parameters << ... >> Operation <no operation> Non-functional Property: ID: N102 NFR Category: Energy Efficiency --> Metric: Battery Discharge Minimum value: 1 Maximum value 3 Most Likely value: 0.4 Parameters << ... >> Operation <no operation> Non-functional Property: ID: N103 NFR Category: Performance --> Metric: Response Time Minimum value: 25 Maximum value 100 Most Likely value: 40 Parameters << ... >> Operation <no operation> </pre>	<pre> Non-functional Property: ID: N105 NFR Category: Movement_Efficiency --> Metric: Speed Minimum value: 0.1 Maximum value 0.4 Most Likely value: 0.4 Parameters << ... >> Operation <no operation> Non-functional Property: ID: N106 NFR Category: Energy Efficiency --> Metric: Battery Discharge Minimum value: 1 Maximum value 3 Most Likely value: 1.2 Parameters << ... >> Operation <no operation> Non-functional Property: ID: N107 NFR Category: Performance --> Metric: Response Time Minimum value: 30 Maximum value 100 Most Likely value: 50 Parameters << ... >> Operation <no operation> </pre>
(A) NFR specification	(B) NFR specification

```

Dependency Association

RG101 -> N101 NFR Category: Movement_Efficiency --> Metric: Speed Dependency Value 9
RG101 -> N102 NFR Category: Energy Efficiency --> Metric: Battery Discharge Dependency Value 7
RG101 -> N103 NFR Category: Performance --> Metric: Response Time Dependency Value 9
RG102 -> N105 NFR Category: Movement_Efficiency --> Metric: Speed Dependency Value 8
RG102 -> N106 NFR Category: Energy Efficiency --> Metric: Battery Discharge Dependency Value 7
RG102 -> N107 NFR Category: Performance --> Metric: Response Time Dependency Value 8

```

(C) FR-NFR Dependency specification

FIGURE B3 Non-functional parameter specification. (A) NFR specification, (B) NFR specification, (C) FR-NFR dependency specification.

```

Contexts:

Contexts-NFR Association

ID: C101 Name: Obstacle Count Values: 1

Impacted NFR: N101 NFR Category: Movement_Efficiency --> Metric: Speed
N102 NFR Category: Energy Efficiency --> Metric: Battery Discharge
N103 NFR Category: Performance --> Metric: Response Time N105 NFR Category: Movement_Efficiency --> Metric: Speed
N106 NFR Category: Energy Efficiency --> Metric: Battery Discharge
N107 NFR Category: Performance --> Metric: Response Time

Contexts-NFR Association

ID: C104 Name: Obstacle after pick up Values: 1

Impacted NFR: N105 NFR Category: Movement_Efficiency --> Metric: Speed
N106 NFR Category: Energy Efficiency --> Metric: Battery Discharge
N107 NFR Category: Performance --> Metric: Response Time

Scenario:

Scenario ID: S3 Contexts: C101 - Obstacle Count : 1 || C104 - Obstacle after pick up : 1 ||

Scenario-NFR Impact:

Scenario ID: S3 NFR: N105 NFR Category: Movement_Efficiency --> Metric: Speed Min Value: 0.1 Max Value: 0.306
Most Likely Value: 0.3
Scenario ID: S3 NFR: N106 NFR Category: Energy Efficiency --> Metric: Battery Discharge Min Value: 1 Max Value: 3
Most Likely Value: 1.5
Scenario ID: S3 NFR: N107 NFR Category: Performance --> Metric: Response Time Min Value: 50 Max Value: 100
    
```

FIGURE B4 Context and scenario DSL.

```

Warning: Scenario S3 The NFR pair EnergyEfficiency-N102-Performance-N103 are in conflict. They are at low risk. The impact relationship between them is linear. The initial expected values are : 0.97 and 0.7
Warning: Scenario S3Performance-N103-Safety-N101 are in conflict. They are at low risk. The impact relationship between them is linear. The initial expected values are : 0.7and 0.72 respectively. For every in
Warning: Scenario S3 The NFR pair EnergyEfficiency-N106-Performance-N107 are in conflict. They are at low risk. The impact relationship between them is linear. The initial expected values are : 0.77 and 0.65
Warning: Scenario S3Performance-N107-Safety-N105 are in conflict. They are at low risk. The impact relationship between them is linear. The initial expected values are : 0.65and 0.83 respectively. For every in
    
```

FIGURE B5 NFR conflicts.

```

For Goal RG101 - Objective function is-  $9w_{s1} + 7w_{B1} + 9w_{R1}$ 
For Goal RG102 - Objective function is-  $8w_{s2} + 7w_{B2} + 8w_{R2}$ 
Range constraint is  $0 \leq w_{s1}, w_{B1}, w_{R1}, w_{s2}, w_{B2}, w_{R2} \leq 1$ 
Conflict constraint:  $0 \leq w_{s1} + w_{R1} + M - M * 0.22 \leq 2$  where M value lies in the range 0.1 - 0.22
 $0 \leq w_{B1} + w_{R1} + M - M * 0.1999 \leq 2$  where M value lies in the range 0.1 - 0.1999
 $0 \leq w_{s2} + w_{R2} + M - M * 0.3299 \leq 2$  where M value lies in the range 0.1 - 0.35
 $0 \leq w_{B2} + w_{R2} + M - M * 0.15 \leq 2$  where M value lies in the range 0.1 - 0.15

ws1: Value of NFR101, wB1: Value of NFR102, wR1: Value of NFR103
ws2: Value of NFR105, wB2: Value of NFR106, wR2: Value of NFR107
    
```

FIGURE B6 Multiobjective optimization problem.