From UML/MARTE Models of Multiprocessor Real-time Embedded Systems to Early Schedulability Analysis based on SimSo Tool

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Abstract: The increasing complexity of Real-Time Embedded Systems (RTES) should be met with equally sophisticated design methods. The recent Unified Modeling Language (UML) profile for Modeling and Analysis of Real-Time Embedded systems (MARTE) is well adapted for systems modeling. However along with the variety of schedulability analysis tools, bridging the gap between design models and meta-models of the documented scheduling analysis tools becomes an important issue.
In this paper, we discuss a Model To Text (M2T) transformation for enabling the derivation of schedulability analysis models from UML/MARTE models. The generated model for schedulability analysis represents an input for an analysis tool. As a proof of concepts, we present the implemented code and experimental results.

1 INTRODUCTION

The spread of technology and the industry requirements have pushed designers to switch from simple monoprocessor architectures to more complex parallel multiprocessor architectures. Considering multiprocessor systems leads to an increasing trend of RTES design, which requires rigorous methodologies to reduce the designer's effort and avoid systems failures. A prominent effort has been focused on the use of Model Driven Engineering (MDE) (Schmidt, 2006) and high-level modeling languages such as UML/MARTE profile (OMG, 2008) to automate the design flows and raise the abstraction level.
On the other hand, designers are interested in verifying the temporal correctness of their studied systems at early design stages to be reassured that no deadline may be missed. In this context, the schedulability analysis is used to validate the temporal behavior of systems scheduled using monoprocessor or multiprocessor scheduling approaches.
Regarding multiprocessor scheduling, three approaches are available in the literature; the partitioned scheduling approach, the global scheduling approach and the semi-partitioned one (Dorin et al., 2010).
The partitioned scheduling approach consists on statically assigning each task to be executed on only one processor. Using this strategy comes to using monoprocessor scheduling approach, since each task may be allocated to only one processor. In a partitioned scheduling context, tasks are not allowed to migrate inter-processors.
While adopting a global scheduling approach, tasks are dynamically allocated to processors and they are allowed to migrate inter-processors improving then Central Processing Units (CPUs) occupation. While using this approach, a full migration of tasks is allowed. Consequently, an attention must be given to the cost of preemption and context switching as well as the number of cache misses due to the transferring of tasks from one computing resource to another one.
Under the semi-partitioned scheduling approach, most tasks are assigned to be executed on specified processors like in the partitioned scheduling approach. Nevertheless, tasks that may not be assigned to a single processor are allowed to migrate inter-processors. This approach enables a restricted task migration to maximize CPU occupation and reduce context switching costs.
Regardless the used scheduling approach, the schedulability analysis has always been an important issue that has been widely studied during the last years. Nevertheless, there are still many open issues regarding this context. In fact, due to the variety of schedulability analysis tools coupled with the ever growing complexity of RTES, there is still a need to automate the early schedulability analysis step to reduce designers' effort. Researchers' attention has been then focused on the transformation of systems models into analysis tools meta-models to analyze

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systems, which are scheduled using monoprocessor and multiprocessor scheduling approaches.
Nevertheless, considering the multiprocessor scheduling, the documented automatic schedulability analysis approaches have addressed only the partitioned and global scheduling approaches.
In this context, we propose an automatic schedulability analysis for systems that are scheduled using semi-partitioned and global scheduling approaches.
MDE is used in this context to raise the abstraction level and automate the schedulability analysis step.
The remainder of this paper starts with motivation and related works in section 2. Section 3 gives an overview of high-level methodologies and analysis tools for early schedulability analysis. In section 4, the proposed process for automatic schedulability analysis at early design stages is highlighted. To validate our proposal, a case study is performed in section 5. Finally, conclusions and future works are given in section 6.

2 MOTIVATION AND RELATED WORK

Checking if RTES meet their timing requirements at early design stages is extremely important to avoid systems failures. In this context, a wide number of research works have been proposed (Zhang and Burns, 2009)(Abdeddaïm et al., 2014)(Lee and Shin, 2013). On the other hand, along with the variety of schedulability analysis tools, the schedulability analysis is still considered as an important issue that needs to be managed properly at a high-level of abstraction to reduce designers' effort.
In fact, each schedulability analysis tool is based on an input meta-model that encloses all the required information for schedulability analysis step.
An input meta-model may be defined using UML, SysML, MARTE, XML, etc.
Since input meta-models differ from one analysis tool to another, some research works have been focused on the building of specific models that represent input for the adopted analysis tools such as in (Jensen, 2009). In this proposal, authors have used MARTE to build a specific model that represents an input for MAST tool. This methodology has been used to support only monoprocessor systems. Moreover, the construction of input models for analysis tools has been done manually. With this regard, other research works have been focused on the automatic built of analysis models through a transformation of systems models to schedulability analysis meta-models.
This model transformation offers automatic schedulability analysis step and fosters the independence of the design flow towards the used analysis tools.
In this context, a Model To Model (M2M) transformation has been performed in (Hagner and Huhn, 2008) to establish an early schedulability analysis of systems using SymTA/S tool (Henia et al., 2005). MARTE profile has been used in this context to annotate models with timing requirements. Activity diagrams annotated through Schedulability Analysis Modeling (SAM) have been transformed to SymTA/S tool meta-model. In the same context, OPTIMUM methodology has been provided in (Mraidha et al., 2011) for early schedulability analysis of systems modeled using MARTE sub-profiles mainly Generic Resource Modeling (GRM) and SAM.
The models transformation that has been proposed in this methodology enables generating concurrency models that may be analyzed and validated using COTS schedulability analysis tools. OPTIMUM has been tested in the case of monoprocessor systems.
In (Medina and Cuesta, 2011), the MARTE profile has been used to model temporal requirements of multiprocessor systems. Built models are then transformed to cheddar tool meta-model to establish an early schedulability analysis for multiprocessors systems while considering partitioned scheduling.
In the same context, a model to model transformation from an activity diagram to Petri Net tool has been proposed in (HadjKacem et al., 2012) to establish an early schedulability analysis of RTES. MARTE/SAM sub-profile has been used to annotate the dynamic view. The multiprocessor scheduling regarding the partitioned scheduling approach has been supported.
In (Naija et al., 2015), an early schedulability analysis for real-time systems has been proposed while using MDE concepts. To perform this step, a model to model transformation has been performed to transform an activity diagram annotated with SAM to Petri Nets tool meta-model. Only the partitioned scheduling has been supported in this proposal.
In (Rubini et al., 2013), an early schedulability analysis from AADL models is performed while using cheddar tool. In this proposal, cheddar has been extended to support global scheduling, but it stills does not support semi-partitioned scheduling.
In previous cited research works for automatic schedulability analysis at early design stages, monoprocessor and multiprocessor scheduling have been supported. Nevertheless, considering the multiprocessor scheduling, only the partitioned or global scheduling approaches have been addressed. No attention has been given to the semi-partitioned scheduling approach. With this regard, we propose in this paper an early schedulability analysis for semi-

partitioned and global scheduling. Our proposal is based on the use of MDE concepts and UML/MARTE profile for a high-level automatic schedulability analysis. Our main goal is to establish models transformation in order to reduce the gap between systems models and schedulability analysis tools meta-models.

3 HIGH-LEVEL METHODOLOGIES AND SCHEDULABILITY ANALYSIS TOOLS FOR AUTOMATIC SCHEDULABILITY ANALYSIS OF MULTIPROCESSOR SYSTEMS

While dealing with complex systems, the use of high-level languages and techniques reduces designers' effort and overcomes the design challenges.
In this section, we give an overview of the used languages, techniques and tools to establish a high-level schedulability analysis step.

3.1 MDE

The Model Driven Engineering (Schmidt, 2006) is a software development methodology considered to be an effective solution that simplifies the design process since it focuses on the abstract representation of domains rather than on computing concepts such as algorithmic concepts. The promoted idea of the MDE paradigm is to use models at different level of abstraction while designing systems to raise the abstraction level of systems specification and increase the automation of their development. MDE is based on three main concepts which are meta-model, model and model transformation.
A model is often specified using Domain Specific Language (DSL) that can be graphical or textual such as UML, MARTE, etc. In fact, different transformation techniques are available in the literature such as M2T and M2M.
The M2T type, which represents a mapping from a model to a text, is based on existing parsers (such as XML/XSLT) that are based on programming languages (JAVA) or mapping templates (JET/ACCELEO). Regarding the M2M technique, it uses mapping languages (ATL or Kermeta) to translate a meta-model to another meta-model while adopting a syntactic and semantic analysis.
In our proposal, we adopt the M2T transformation to transform the system model into a schedulability analysis meta-model and then establish an automatic schedulability analysis at early design stages.
In this context, we have implemented an ACCELEO template (ECLIPSE, 2008) to perform this transformation.

3.2 MARTE

MARTE is a profile adopted by the Object Management Group (OMG) to replace the UML Profile for Schedulability, Performance and Time (SPT) (OMG, 2002). This profile defines foundations to support specification, design and verification of RTES. It provides a common way of modeling both hardware and software aspects. MARTE is considered as one of the most commonly used high-level language for complex systems modeling. Considerably, it models properly temporal requirements of RTES.
MARTE encloses different sub-profiles providing a big set of stereotypes and attributes to annotate models with data, which are required to establish specific analysis. Among these sub-profiles, we cite Generic Resource Modeling (GRM), Software Resource Modeling (SRM), Hardware Resource Modeling (HRM), Generic Quantitative Analysis Modeling (GQAM), Performance Analysis Modeling (PAM), SAM, etc.
What is worthwhile to note is that originally MARTE supported only monoprocessor and partitioned scheduling.
In this context, extensions of MARTE have been documented to support both semi-partitioned and global scheduling (Magdich et al., 2012)(Magdich et al., 2013a)(Magdich et al., 2013b). These extensions are used in this paper to model the studied system.

3.3 Schedulability Analysis Tools for Multiprocessor Scheduling

To validate temporal requirements of critical applications, various tools for scheduling analysis have been documented in the literature such as MAST (Gonzalez Harbour et al., 2001), Cheddar (Singhoff et al., 2004), (Rubini et al., 2013), RealtssMP (Ramirez et al., 2012), STORM Simulation TOol for Real-time Multiprocessor scheduling (Urunuela et al., 2010), Colored Petri Nets (CPN) tools (cpn, 2015), etc.
The cited scheduling analysis tools may be used to analyze systems which are scheduled using monoprocessor or multiprocessor scheduling approaches.
Considering multiprocessor scheduling approaches, only the partitioned and global scheduling approaches are supported by these tools. On the other hand, these tools are designed to validate, test and analyze systems without handling with direct overheads such as

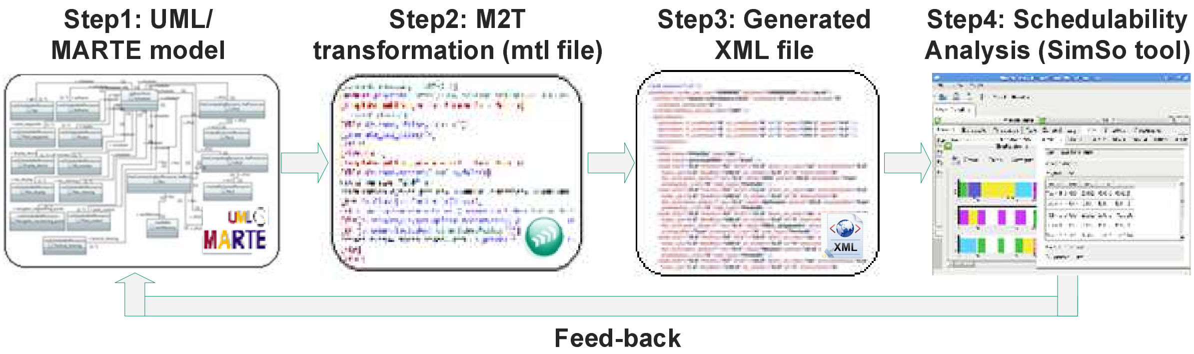

Figure 1: Early schedulability analysis methodology based on MDE and Simso tool.

scheduling overheads and context switching.
To deal with this issue, SimSo tool for Simulation of Multiprocessor Scheduling with Overheads (Chéramy et al., 2014) has been proposed. This open source tool is used in our proposal since it supports both semi-partitioned and global scheduling. The input of the considered tool is an XML file that encloses all the needed criteria for temporal verification.
Consequently, the challenge addressed in this paper is the transformation of a MARTE model supporting semi-partitioned or global scheduling to SimSo meta-model for early and automatic schedulability analysis.

4 PROPOSED METHODOLOGY FOR AUTOMATIC SCHEDULABILITY ANALYSIS AT AN EARLY STAGE

The proposed methodology enables automatic schedulability analysis of RTES at early design stages while supporting both semi-partitioned and global scheduling approaches. Figure 1 shows the different steps adopted by our methodology to check the temporal correctness of RTES.
To validate temporal correctness of RTES, SimSo tool that accepts only XML file as input is used in our proposal.
Given a system model annotated through MARTE profile and mainly using GRM and GQAM (Step1), a M2T transformation must be performed to translate the system properties from the MARTE model to the meta-model of SimSo tool. In this context, we have implemented an ACCELEO template (Figure 2) to support this transformation (Step2).
This template implements transformation of MARTE concepts to SimSo meta-model concepts.
The execution of the implemented template allows the generation of an XML file, which contains the system properties (Step3).

This file will be entered to the SimSo tool for schedulability analysis check (Step4). In case of non schedulability, a feed-back has to be done for MARTE model rectification. Table1 shows some of transformation concepts from MARTE to SimSo.

Table 1: MARTE to SimSo transformation concepts.

	MARTE	**SimSo**
Processor stereotypes and annotations	«HwProcessor» «HwComputing Resource»	processor
	«name»	name
	«speedFactor»	speed
Tasks stereotypes and annotations	«SwSchedulable Resource»	task
	«isPreemptable»	preemptible
	«type»	task_type
	«periodElements»	period
Scheduler stereotypes and annotations	«GaExecHost» «Scheduler»	sched
	«otherSchedPolicy»	class

For example, a class annotated through the stereotype «HwProcessor» or «HwComputingResource» (or both of them) models a processor. It is transformed to an element named *processor*.
«speedFactor» is an attribute of the stereotypes «HwProcessor» and «HwComputingResource». It is transformed to the element *name*.
«SwSchedulableResource» is used to annotate a class which models a task. It is transformed to the element *task*. «isPreemptible» is a MARTE attribute that is used to specify whether a task may be interrupted. It is transformed to the element *preemptible*.
The stereotypes «GaExecHost» and «Scheduler» are used to annotate a class, which models a scheduler.

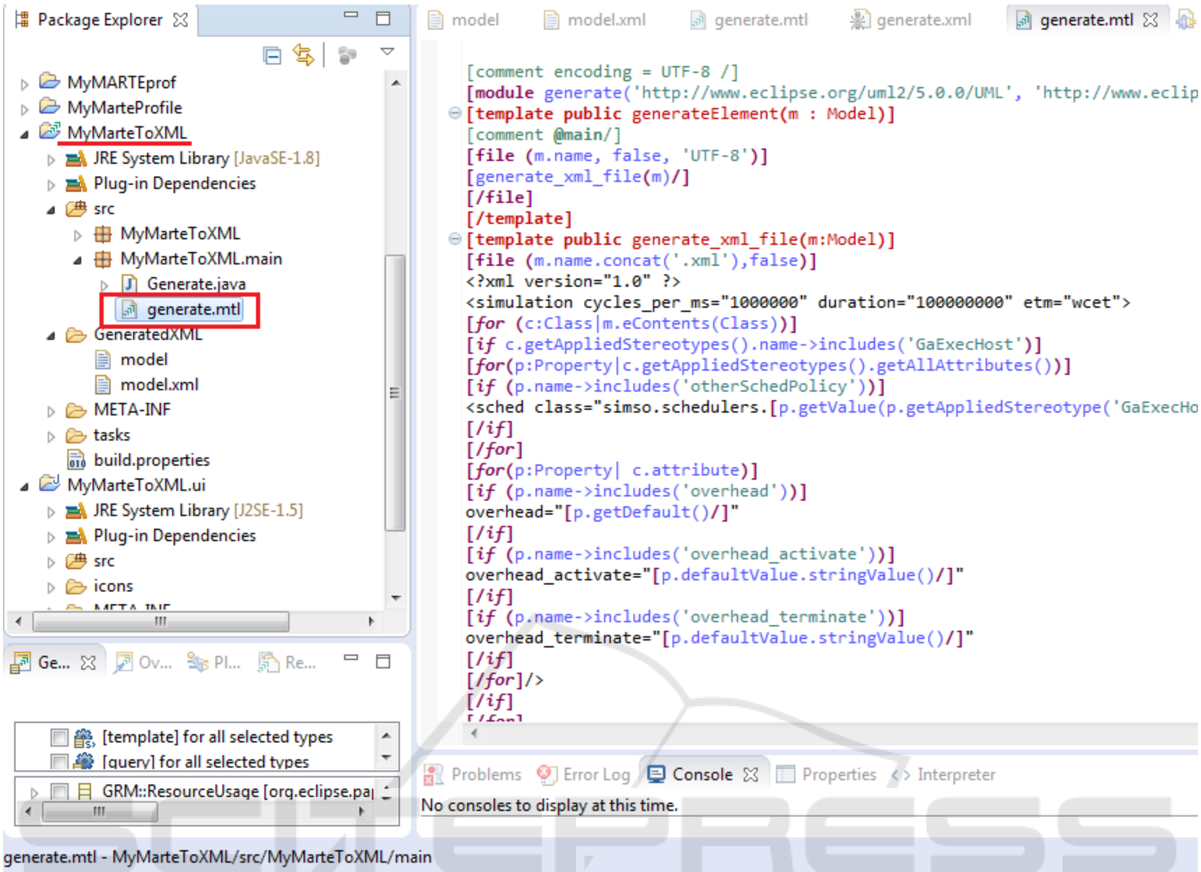

Figure 2: ACCELEO template for MARTE to XML transformation.

Figure 3: ECLIPSE plugin for automatic MARTE to XML transformation.

These stereotypes are transformed to the element *sched*. The attribute «otherSchedPolicy» is used to specify the name of the scheduling policy. It is transformed to the element *class*. To automate any model to text transformation from MARTE to XML model, we have transformed the implemented ACCELEO code into an ECLIPSE plugin (Figure3).

5 CASE STUDY

To evaluate the proposed methodology for early schedulability analysis, we have considered the Real-Time CORBA avionics application (Madl, 2009). The system application is composed of eleven periodic and independent tasks such that every task is characterized by a WCET (Worst Case Execution Time), a period, a priority and a deadline (Table 2).
These parameters will be used as input for the schedulability analysis step. Thus, they have been specified in the MARTE model of CORBA system.
These properties must be entered in the tasks classes annotated through «SwSchedulableResource» stereotype. Other parameters, such as the scheduling type (static or dynamic scheduling), must also be specified to handle this step. The considered application is mapped to a preemptive execution platform composed of three identical processors running at 4GHz using 6GB three-channel RAM. The modeling of the studied system using UML/MARTE is exposed via Figure 4. As specified in Table 2, Gps task is periodic, which is indicated through the attribute «type:

Table 2: Tasks parameters for CORBA application.

Task	WCET	Deadline	Period	Priority
Gps	21	100	5	41
Airframe	53	100	15	42
Pilot_waypoints	37	100	5	43
Routes	18	100	10	44
Display_device	26	150	10	47
Af_monitor	33	120	5	49
Nav_display	14	80	5	48
Nav_steering	69	100	5	46
Navigato _navsteering _points	42	150	10	45
Pilot _control	43	100	20	50
Tactical _steering	38	80	10	51

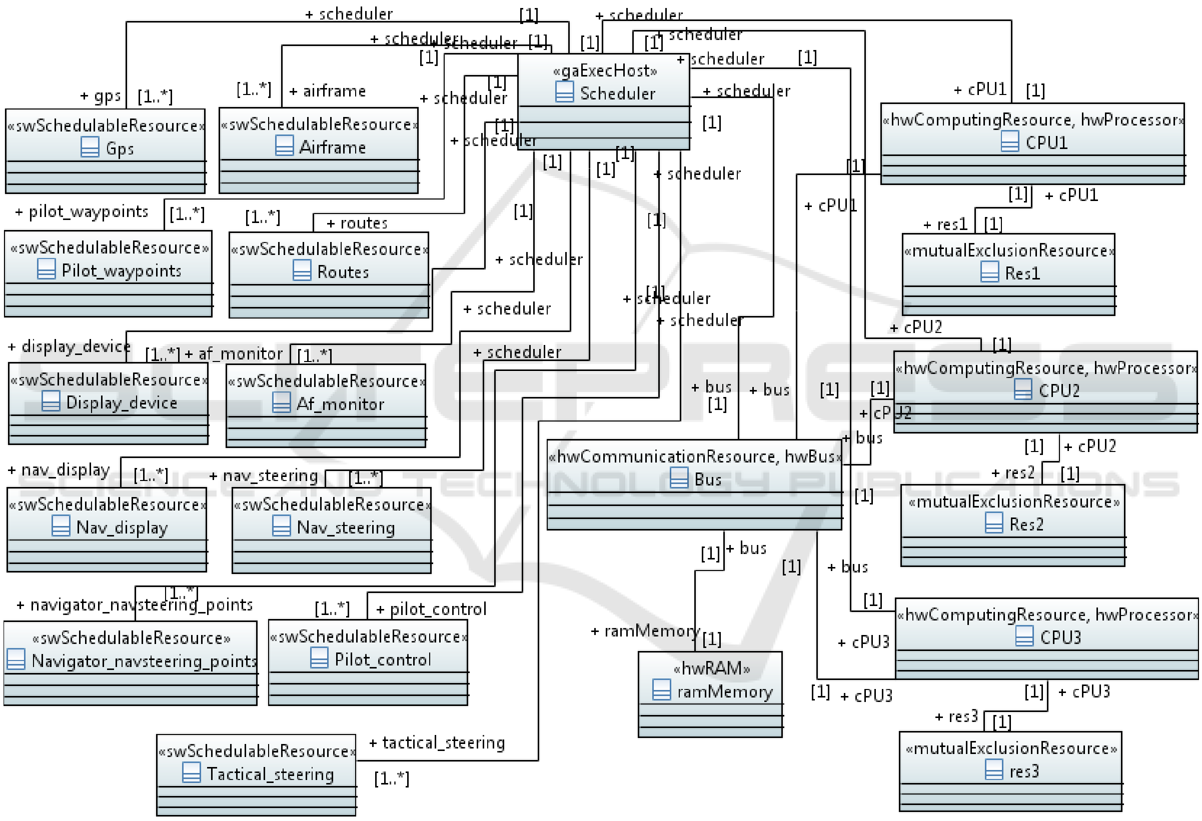

Figure 4: The static view of the CORBA application.

ArrivalPattern» that is set to «periodic(5,ms)».
The priority of Gps task is 41, which is specified through the attribute «priority:NFP_Integer [0..*] =priority». The deadline and period of Gps task are respectively specified through «deadline:NFP _Duration[0..*] = deadline» and «period:NFP_Duration[0..*]= period» such that the deadline and the period are respectively set to (100,ms) and (5,ms).
The activation date of Gps is set to 0 ms through «activationDate:NFP_ Duration [0..*]=(0,ms)». The required scheduling type is static, which is mentioned by setting the value of «isStaticSchedulingFeature» to «true». The used scheduling algorithm is EDZL (Lee and Shin, 2013). Using our ECLIPSE plugin for MARTE to XML transformation, the MARTE model for CORBA application has been transformed into an XML file that will be entered to SimSo tool. Figure 5 shows the contents of the generated XML file under ECLIPSE. The generated XML file has been entered

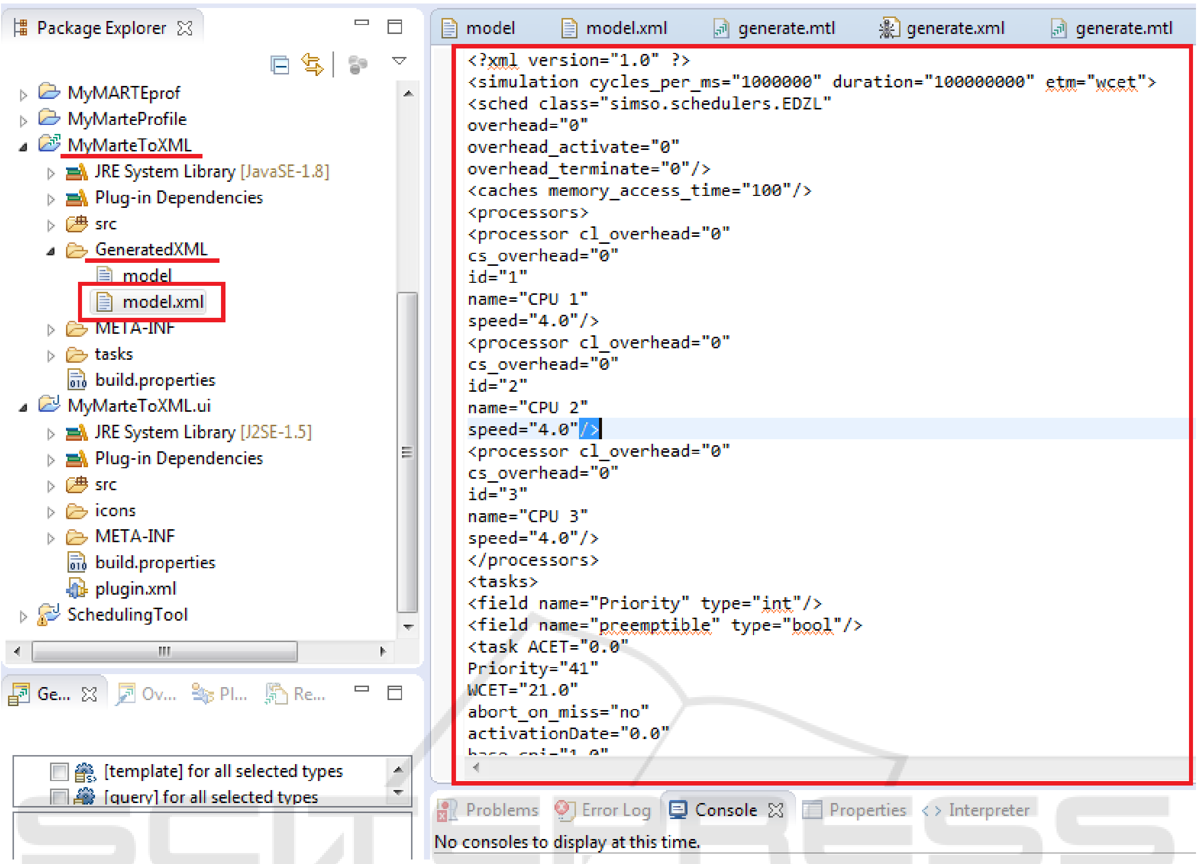

Figure 5: Generated XML file after a M2T transformation.

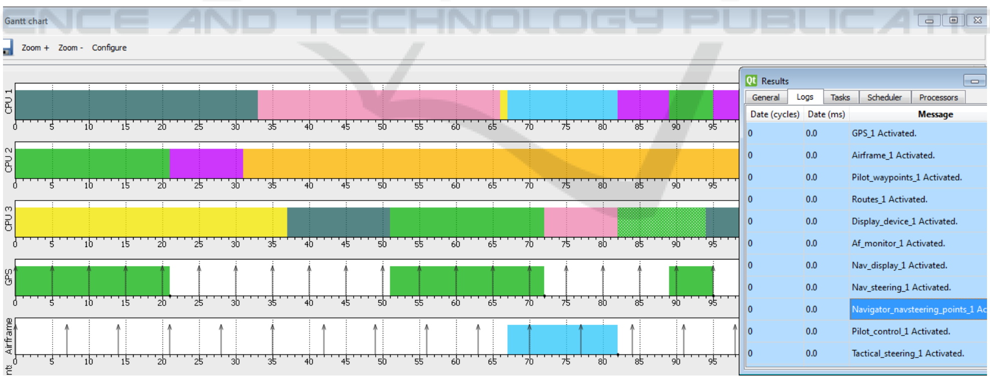

Figure 6: Simso tool schedulability analysis report.

into SimSo for schedulability analysis of CORBA application. Results have shown that the system is schedulable (Figure 6).

6 CONCLUSIONS

Throughout this paper, we have proposed an MDE-based automatic schedulability analysis at early design stages. Based on a M2T transformation from MARTE model to SimSo tool meta-model, properties of the studied system were translated from MARTE model to an XML file representing the input of SimSo. A main key of this proposal is that is supports analysis of systems, which are scheduled using semi-partitioned and global scheduling approaches.

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