Extending the Software Tool TimeNET by Power Consumption Estimation of UML MARTE Models

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Keywords: UML, MARTE, Petri Net, Power Consumption, System Design, Modeling Tool TimeNET.

Abstract: This paper presents an extension of the software tool TimeNET, which supports modeling and analysis of stochastic Petri nets. The new extension implements a previously proposed method for power consumption modeling and evaluation based on extended UML models. Two new net classes have been developed to support the necessary operational and application models and edit them in the graphical user interface. Several stereotypes of the UML Profile for Modeling and Analysis of Real-Time and Embedded Systems (MARTE) have been added to extend the information about power consumption of system and application states. The two UML models are then automatically transformed into a stochastic Petri net. Power consumption of the system can be predicted by standard Petri net analysis modules of TimeNET. An example of an industrial control system is provided.

1 INTRODUCTION

Energy consumption is an increasingly important non-functional property of embedded systems and in automation in general. Design decisions have to be based on a trade-off between energy use and other requirements. It is thus important to evaluate the effect of architectural and other design decisions in all phases of the development process based on a good prediction of the energy consumption of an embedded system. In this work, we concentrate on early design steps, in which major architectural decisions are made, which may have a significant impact on the overall system's energy consumption. Modeling methods should be developed for discrete automation systems in such a way that the energy consumption, beside other parameters, can be modeled, estimated, and finally reduced.

The Unified Modeling Language (UML) (Object Management Group (OMG), 2012) is an industry standard for describing software systems. However, it is not intended to describe non-functional system properties equally well, as there are no constructs for quantitative properties. Domain profiles of the UML have been developed for this task, namely, the MARTE profile (Modeling and Analysis of Real-Time and Embedded Systems (Object Management Group (OMG), 2011)) as a successor of the UML SPT profile (Object Management Group (OMG), 2005).

UML models adopting the MARTE profile contain the necessary information for energy consumption estimation. However, they are not usable directly, as UML models are not semantically well-defined for a specification of the resulting stochastic process. For this work, we proposed UML models to be transformed into a model for which analysis algorithms exist and, namely, into extended deterministic and stochastic Petri nets (eDSPN) (German, 2000), such that the behavior and the properties are preserved. This was motivated by an earlier work by a former colleague, in which single extended UML state chart models describing reliability aspects of a system were transformed into uncolored SPNs for their analysis (Trowitzsch and Zimmermann, 2005; Trowitzsch, 2007).

The proposed method has been described in detail in (Shorin et al., 2012), covering how the energy consumption of a microcontroller can be estimated by dividing the system into hardware and software parts. The hardware part remains the same for all applications, and is thus described in an *operational model* and specifies all possible modes of the system, the possible state changes, and their associated power consumption (as well as transition times, if applicable).

On the other hand, the effect of the controlling software is captured in one or more *application models*. It describes which steps are taken and what time

Shorin D. and Zimmermann A..
Extending the Software Tool TimeNET by Power Consumption Estimation of UML MARTE Models.
DOI: 10.5220/0005096700830091
In *Proceedings of the 4th International Conference on Simulation and Modeling Methodologies, Technologies and Applications* (SIMULTECH-2014), pages 83-91
ISBN: 978-989-758-038-3
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is spent in which mode, and may have stochastic behavior (interrupts, for instance). Thus, it contains information about the operational states used in the specified system and their duration. The model distinction follows the principle of separation of concerns in (software) engineering of complex systems. This type of distinction can be found in other fields as well, for instance in manufacturing systems, where a similar relation exists between structure (machines, transport routes) and work plans (Zimmermann and Hommel, 1999).

The two models together contain all the necessary information for predicting the power consumption. In this paper, we present an extension of the software tool TimeNET (Zimmermann, 2012) that makes possible an automatic combined transformation into an SPN. The resulting model can then be used to estimate the power consumption of the system with stationary analysis.

A related approach similar to the one of (Trowitzsch and Zimmermann, 2005; Trowitzsch, 2007) is taken in (Callou et al., 2008), in which enriched UML models are translated into stochastic Petri nets. The main difference to our work is the distinction between the two aspect models and their integration during transformation. Another approach with similar goals is presented in (Andrade et al., 2009), where a UML model is translated into a colored Petri net (CPN) description as supported by the CPN tools (Jensen et al., 2007). However, the resulting model tends to be rather complex and the CPN interpretation does not support a natural notion of (stochastic) time similar to the widely accepted model class of stochastic Petri nets.

The paper is structured as follows. Section 2 briefly recalls the implemented method. Section 3 describes the tool environment TimeNET and the implemented extension. An example is presented in Sec. 4, before some final conclusions and acknowledgments are given.

2 METHOD DESCRIPTION

We consider each embedded system to be consisting of hardware and software parts. The hardware part of the system is reflected in the *operational model*. In this model, all possible states and transitions of the system itself (without application-dependent specifics) must be described. One embedded system can be described by means of only one operational model, as the hardware part of an embedded system are more stable than the software. In case of a change in the components of the embedded system under consideration, a new or adapted operational model is needed.

The software part of the system is described in the *application model*. This model contains information about the states of each of the specified programs running on the system, their waiting times and duration. Any modification of the software part of the system must be reflected in the application model, yet the operational model remains the same. Thus, any embedded system can be represented by means of a single operational model and an set of application models. For building both models, we use the means of one of the behavioral UML diagrams – State Machine Diagram – extended with the stereotypes of the MARTE profile.

2.1 Operational Model

This model contains all the necessary information for analyzing the (hardware) system under consideration. All possible states and transitions of the system should be described, and all state names have to be unique to avoid ambiguities as the later application model identifiers correspond to them.

The states are described by means of the <<*ResourceUsage*>> stereotype of the MARTE profile. This package was specially created for considering the resource consumption in the system. Two attributes are taken into account: *execTime* and *powerPeak*. The first one reflects the duration of staying in each state (in seconds), while the second represents the power required for the state (in Watt).

All the simple states must have an attribute *powerPeak* that specifies the power consumption of the simple states. The attribute *execTime* should be applied if the (default) execution time for some simple states is known and remains the same regardless of the application executed.

2.2 Application Model

At the second stage of the proposed method, an application model has to be created. It contains information about the states used in the specified program and their duration. The order of transitions between the modes must comply with the order specified in the operational model. However, the states for which both the power consumption and the execution time are given in the operational model may be skipped in the application model. For the correspondence detection between these two models, the modes implemented in the application model must be named identical to the states of the operational model. It is required to mark the initial state of the system.

The attribute *execTime* has to be applied by all simple states if it is not stated in the operational model. It specifies the execution time of the simple states. If the execution time is given in both operational and application models, the value from the application model will be taken for the analysis. This decision lets the user overwrite the default execution time if necessary.

The attribute *prob* has to be given for all the states which immediately follow the choice pseudostate. It specifies the execution probabilities for these following states.

As it is impossible to set attributes by pseudostates, transitions going out of the choice pseudostate must lead only to the simple states. This is a known UML problem. If this rule is not followed, the system model will be incompletely specified.

2.3 Transformation Rules

For analyzing the energy consumption of the system, we combine application and operational models and convert them into a Petri net. For this operation, we take the application model as the basic one. The operational model delivers the missing information, such as power consumption, missing states, and their duration.

For each simple state of the application model, there must be a certain simple state in the operational model. Simple states of the operational model can be either linked to one, several, or no simple states in the application model.

States and their outgoing transitions are transformed simultaneously, because UML transitions after different state types are transformed either into exponential or immediate transitions.

The rules used to transform UML models into a Petri net are described in detail in (Shorin et al., 2012).

Each UML simple state of the application model with its outgoing transition is transformed into a Petri net place and a transition if such transition between two states exists in the operational model. If this is not the case and such transition does not exist in the operational model, the path must be found through the other states in the operational model, for which all the necessary information (execution time and power consumption) is given. If more than one way exists, the software tool warns the user and chooses the one in which the system consumes less power. The well-known Dijkstra algorithm (Dijkstra, 1959) was implemented in the software tool for this task.

Each execution time value of the simple states is transformed into the attribute *delay* of the appropriate exponential transition of the Petri net.

Each UML simple state of the application model has its power consumption. The relevant value is taken from the linked simple state of the operational model. The formula for power consumption estimation represents a sum of the probabilities of the state activation multiplied with its power consumption values. The calculation result is then added as a performance measure object of the Petri net in TimeNET.

$$measure = \sum_{i=1}^{\infty} P(\#state_i > 0) \cdot powerPeak(\#state_i) \tag{1}$$

Each UML choice pseudostate of the application model is transformed into a Petri net place which is followed only by immediate transitions that model the probabilistic choice.

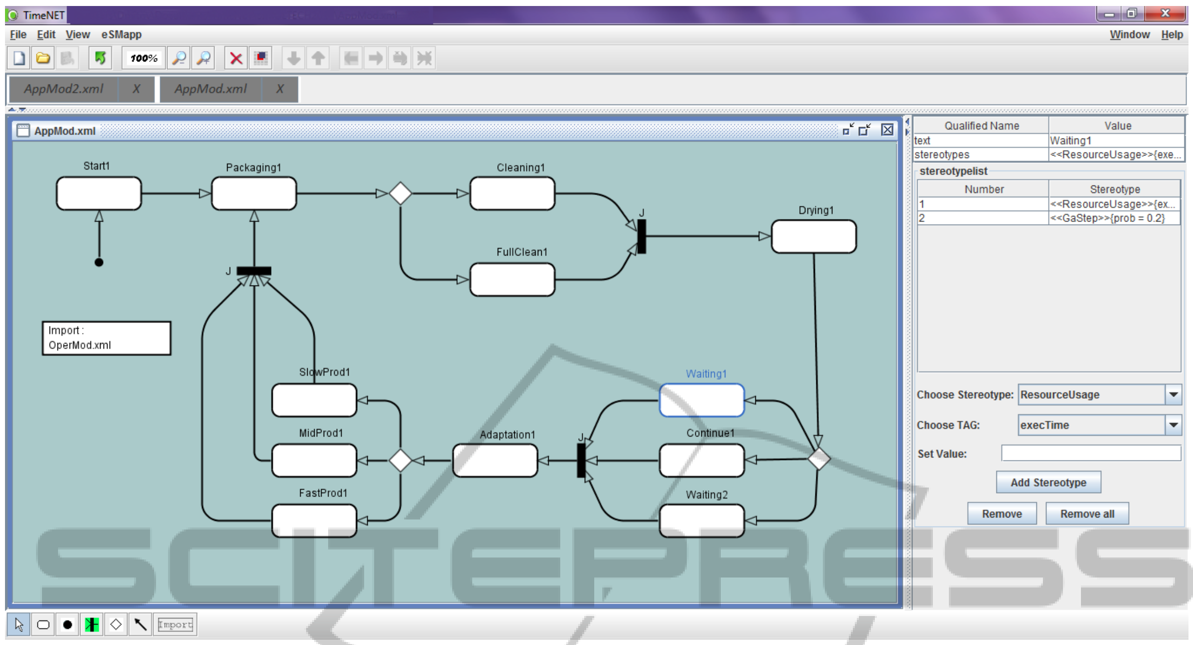
Every UML join pseudostate of the application model is transformed into a Petri net place which is followed by an immediate transition. Each value *prob* of the simple states, which immediately follow UML choice pseudostates, is transformed into the attribute *weight* of the appropriate immediate transition of the resulting Petri net.

Each UML initial state is transformed into a Petri net place which is followed by an immediate transition. The attribute *initialMarking* of the Petri net place is then set to *1*.

After finishing the UML model transformation, the power consumption can be automatically calculated either by a numerical analysis or simulation both in transient and steady-state by algorithms of TimeNET.

3 TOOL IMPLEMENTATION AS A TIMENET EXTENSION

This section presents TimeNET – a software tool for modeling and evaluation of stochastic Petri nets. Subsection 3.1 gives some general information about the software tool. An earlier work added stochastic UML state charts (Trowitzsch and Zimmermann, 2005; Trowitzsch, 2007) to the tool (Trowitzsch et al., 2007). This existing extension was primarily aimed at reliability modeling and evaluation. The current paper presents the further extension of the tool by energy use description and evaluation. The main difference to (Trowitzsch et al., 2007) is the distinction between operational and application models as described in Sec. 2. Subsection 3.2 describes in detail the integration of the new extension into TimeNET, especially corresponding to the two new necessary net classes. The tool functionality is presented in Subsec. 3.3.



Qualified Name	Value
text	Waiting1
stereotypes	<<ResourceUsage>>{exe...

stereotypelist

Number	Stereotype
1	<<ResourceUsage>>{ex...
2	<<GaStep>>{prob = 0.2}

Choose Stereotype: ResourceUsage

Choose TAG: execTime

Set Value:

Add Stereotype

Remove Remove all

Figure 1: Application model built in TimeNET.

3.1 Tool Description

TimeNET (Zimmermann, 2012; German et al., 1995) is a software tool supporting modeling and performance evaluation of stochastic Petri nets, especially for models with non-exponentially distributed firing delays (German, 2000). TimeNET analyses extended stochastic Petri nets and colored stochastic Petri nets. The software also lets the user create UML state charts, which will be then transformed into stochastic Petri nets for the further analysis.

The software tool has been originally built at the Technische Universität Berlin and is being developed by the System and Software Engineering group of the Technische Universität Ilmenau since 2008. The functionality of the software is being continuously advanced, so that it covers more and more aspects of Petri net analysis and related models. The modular tool architecture lets computer engineers extend the program code easily and thus, enlarge the possibilities of the software. The current version of the software 4.2 appeared in May 2014 at the time of the paper writing.

The interactions between components of TimeNET are well described in (Zimmermann, 2012). The central connecting module is the graphical user interface (GUI). It is programmed in Java for portability and uses data and model schemata specified in XML (eXtensible Markup Language). The GUI calls different simulation and analysis algorithms as requested by the user. These components are written in C and C++, often including code generated at run time for efficiency reasons.

After starting the simulation process, the GUI creates a master process. It gathers all the given parameters of the user models and compiles all the necessary information from the GUI. It then starts slave processes which execute the actual simulation. The interaction between GUI and analysis algorithms is realized with data files, while sockets are used between analysis processes. The master process controls interactions between slave processes and, finally, reads the results. These are sent to the GUI where they are presented to the user.

TimeNET can be used in both Linux- and Windows-based operating systems. The GUI (PENG, platform-independent editor for net graphs (Jakop, 2003)) is generic and lets the user easily implement any graph-like modeling formalism. Thus, TimeNET is not restricted to stochastic Petri nets, but can be extended for using other graphs such as UML state charts or automata.

The software can be extended by new net classes which use specific algorithms. While creating a new model in TimeNET, the user chooses the applicable net class and the GUI is being extended by the respective algorithms.

The main window of TimeNET (see Fig. 1) includes a standard menu panel which lets the user work with files, edit models, change the model's view and choose one of the algorithms specific for the current net class. For example, for building the model in

Table 1: Stereotypes and attributes used in the models.

Stereotype	Attribute	Operational model	Application model
<<ResourceUsage>>	powerPeak	mandatory	not applicable
	execTime	optional	mandatory
<<GaStep>>	prob	optional	mandatory

Fig. 1, we used the net class *eSMapp*, one of the two net classes described further in this paper. The detailed information is presented in Subsec. 3.3.

The toolbar below the menu panel contains buttons for the most frequently used commands. The next toolbar from the top lets the user switch between models opened in the software tool. The main part of the window is occupied by the graphical workspace for building models. The model elements which can be used in the given net class are shown below the main window in the icon bar at the left. The panel on the right-hand side serves for changing model element properties and adding attributes.

The user's interaction with the GUI does not differ from common standards. The user chooses an element in the bar at the bottom of the screen and clicks on the workspace to place it. In the mode *select*, which is depicted by a white arrow, the user can move elements in the workspace, edit them and state their parameters in the list on the right-hand side.

3.2 Integration of Energy-Aware State Machines in TimeNET

For estimating power consumption, two new net classes were implemented in TimeNET. Both deal with energy-aware UML state charts (eSM). The operational model is being created within the net class *eSMoper*, the other net class *eSMapp* serves for creating application models such as described in Sec. 2 and previous papers (Shorin et al., 2012; Shorin and Zimmermann, 2013). They have similar structure, but support the differences between two types of models described in Sec. 2. The XML schemata implemented for these net classes are based on the schema for the net class *sSM*, which was created for modeling UML stochastic state machines (Trowitzsch et al., 2007). A necessary subset of UML elements described in Sec. 2 was implemented in the current prototype and can thus be used in the given net classes.

Figure 2 depicts the integration of the net classes *eSMoper* and *eSMapp* into TimeNET. Using the TimeNET GUI, the user can build operational and application models by means of these two net classes. The models will be saved in two XML files. Any application model has to be conceptually linked to an operational model — this relation is provided by the user in the application model (details in Subsec. 3.3).

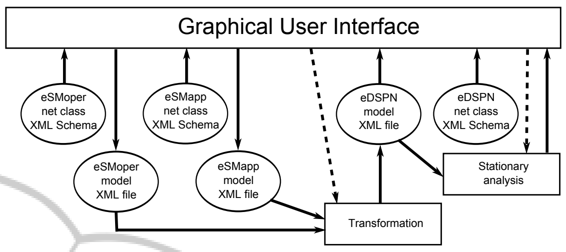


Figure 2: Integration of eSMoper and eSMapp net classes.

Each net class has its specific functions, which are represented in the menu bar. Thus, the user can start the transformation into an *eDSPN* model only while using the net class *eSMapp*. The command starts the conversion based on the rules given in Subsec. 2.3. During this procedure, the information from two models is being merged and a final SPN is thus being created (Shorin et al., 2012). The resulting Petri net belongs to the net class *eDSPN*, the fundamental class of TimeNET, for which analysis and simulation functions are available. The stationary analysis of the Petri net results in the estimated power consumption of the analyzable system.

The net classes *eSMoper* and *eSMapp* provide the user only with the UML state chart elements depicted further in Fig. 3. Thus, they support modeling of simple states, initial, join, and choice pseudostates, as well as transitions. Simple states can be extended by some stereotypes of the MARTE profile. The stereotype <<*ResourceUsage*>> is being used here for specifying power consumption (attribute *powerPeak*) and execution time (attribute *execTime*) of the simple states. The tag *prob* of the other stereotype <<*GaStep*>> serves for setting the probabilities of the states which immediately follow the choice pseudostate. Table 1 indicates the stereotypes and tags supported by the net classes and shows if they are mandatory in operational and application models. Furthermore, state machines built in these two classes must fulfill the conditions given in the method description (Sec. 2).

3.3 Tool Functionality

Figure 1 shows the GUI while creating an application model. The menu panel includes section *eSMapp* which contains functions specific for the net class. Its function *eSMapp to eDSPN* converts two models into

SPN for further analysis. The icon bar on the bottom of the screen includes following modeling elements: mode *select*, simple state, initial, join, and choice pseudostates, state transition, and element *Import*. The last one can be used to set the operational model linked to the current application model.

The TimeNET window while working in the net class *eSMoper* looks similar with two exceptions: The section *eSMoper* of the menu panel does not let the user create an SPN out of the operational model, and the icon bar at the bottom of the screen does not include the element *Import*. The reason for this is that one operational model can be linked to numerous application models.

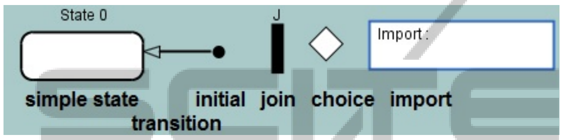


Figure 3: Elements for creating an application model.

Elements which can be used for creating an application model are shown in Fig. 3. A simple state is represented by an empty rectangle with rounded corners. The initial pseudostate is depicted as a small solid black circle. The join pseudostate is shown as a small solid black rectangle with a letter *J* above it, while the choice pseudostate is depicted as an empty rhombus. Transitions are displayed as an arrow directed from the outgoing state to the incoming state. The *Import* specification is represented by an empty rectangle with standard sharp corners. Inside the figure, there is a word *Import* with a semicolon and the name of the file containing the operational model linked to the current application model.

By selecting a simple state in the selection mode, the user can add attributes and change its name in the panel at the right side of the screen (see Fig. 1). Initially, each simple state gets a name which consists of the word ”state” and an ordinal number beginning from zero automatically. The user has the opportunity to change the name in the property *text*. The property *stereotype* is being used for adding attributes to the element. This field can be filled up automatically by using the fields below. The *stereotypelist* demonstrates all the attributes added to the chosen state. In the field *Choose stereotype*, the user can choose between <<*ResourceUsage*>> and <<*GaStep*>> stereotypes. Depending on the choice in this field, the field *Choose TAG* offers to state either execution time in the attribute *execTime* (in the case of the <<*ResourceUsage*>> stereotype) or the state probability in the attribute *prob* (stereotype <<*GaStep*>>). By creating an operational model, the attribute *powerPeak* of the <<*ResourceUsage*>> stereotype is also available for stating the power consumption of the simple state. This attribute is not available in the application model as it is stipulated by the method described in Sec. 2. Table 1 gives an overview of the attributes which can or must be used in both models. In the text field *Set Value*, the user states a value of the chosen attribute. By clicking the button *Add Stereotype*, the chosen attribute will be added to the stereotype list above. The further buttons *Remove* and *Remove all* let the user delete either a single chosen attribute or all of them, respectively.

The element *Import* has an additional property field *filename*, which is used to set the name of the XML file containing the corresponding operational model.

After creating both operational and application model, the user can start the transformation to a Petri net via the menu item *eSMapp* $\rightarrow$ *eSMapp to eDSPN*. TimeNET will ask for the name of the resulting XML file to save the results. After the transformation, the created file containing a new eDSPN should be opened and the *stationary analysis* (menu *Evaluation*) started. The results will be displayed in the field *measure* in the TimeNET workspace. The value gives an estimation of the system power consumption.

4 EXAMPLE

In this section, we show how the possibilities of the presented TimeNET extension are used in practice. In comparison to the example given in (Shorin et al., 2012), we explicitly take not an embedded, but an industrial control system to show the breadth of the method and software application. In this example, we consider component production by a workbench with a main and two reserve motors. Its structure is depicted in Fig. 4.

The workbench gets its first order and is being started (represented by the state *Start*). The process goes through the fictitious state *Continue* (see details below) and the order is adapted. Furthermore, there are three possibilities of producing components depending on performance requirements. The first one is called *Slow production* — it takes 5 minutes to create one unit. By choosing the second mode, one motor more is started and thus, the production speed reduces to 3 minutes. The third possibility is to start two reserve motors and to produce the component in only one minute. The fastest way could be the most preferable one, but the difference between these three modes is also in the power consumption. We assume that the longer it takes the workbench to produce a

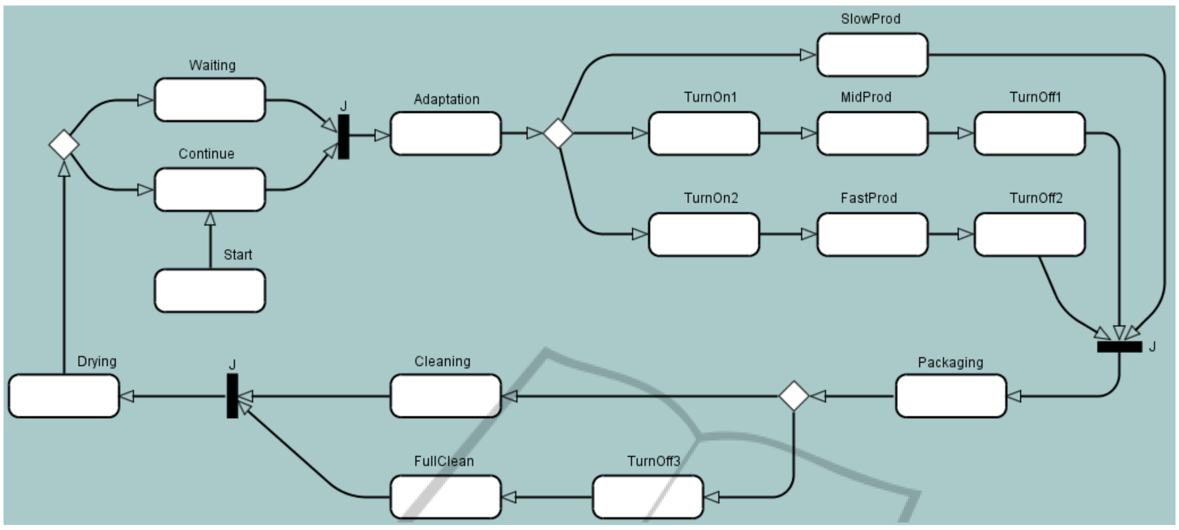


Figure 4: Operational model of the workbench.

unit, the less overall power it needs for this operation. The energy needed for the workbench to function in the first mode is 2.5 watt-seconds, in the second one 3 W·s and in the third – 5 W·s. Thus, the example could be used to show a design trade-off between power consumption and other conflicting non-functional properties of a system. An overview of the attributes related to the states is given in Table 2.

Table 2: Attributes stated in the operational model.

State name	powerPeak, W	execTime, min.
Start	5	2
Waiting	0.1	
Continue	0	0.00001
Adaptation	0.2	0.1
TurnOn1	2	0.2
TurnOn2	4	0.2
SlowProd	0.5	5
MidProd	1	3
FastProd	5	1
TurnOff1	0.1	0.1
TurnOff2	0.2	0.1
TurnOff3	0.1	0.4
Packaging	0.3	0.2
Cleaning	0.3	0.1
FullClean	1	0.5
Drying	0.4	0.1

If one or two reserve motors are used in the production process, it takes extra time and power to turn them on and off (states *TurnOn1, TurnOn2, TurnOff1, TurnOff2*). When the component is produced, it will be packed (*Packaging*). After each procedure, the workbench must be cleaned. Cleaning has two modes: either a normal quick *Cleaning* or a *Full Cleaning* which takes more time and demands the main motor to be also stopped (*TurnOff3*). After that, it takes a little time to dry the workbench (*Drying*). If necessary, the main motor is being started during this process. Thus, the workbench finishes its work on the unit and goes either in the standby mode (*Waiting*) or continues its work without a pause. The value 0.00001 given in the *Continue* state is caused by the requirement for the exponential transitions of Petri net: the *delay* value which here represents the execution time may not be equal to zero. Otherwise, the Petri net will not be properly analyzable. However, this substitution does not influence the end result. The only function of the state *Continue* itself is to be a regular (non-pseudo) state after the choice pseudostate. This restriction of UML was described in Subsec. 2.2.

Figure 4 depicts the operational model built on the basis of the system description above. After that, the user can create an application model. The one used in this example is shown in Fig. 1. When the first order arrives, the workbench starts working (*Start1*). As it is necessary to produce one unit, no matter how quickly it will be, it is enough to simply place a state *Packaging1*. The production mode will be chosen automatically while creating the SPN. The full cleaning mode should take place after each 10 production steps. Thus, the state *Cleaning1* has a probability (*prob*) 90% and *FullClean1* – 10%. After the *Drying*, the workbench continues its work (with the probability of 70%) or has either a short break (1 minute long, 20% probability) or a long break (5 minutes long, 10% probability). These probability values were chosen on the basis of the statistical data. The further choice of the production mode depends on the demand. Though, the longest mode (*SlowProd1*) is

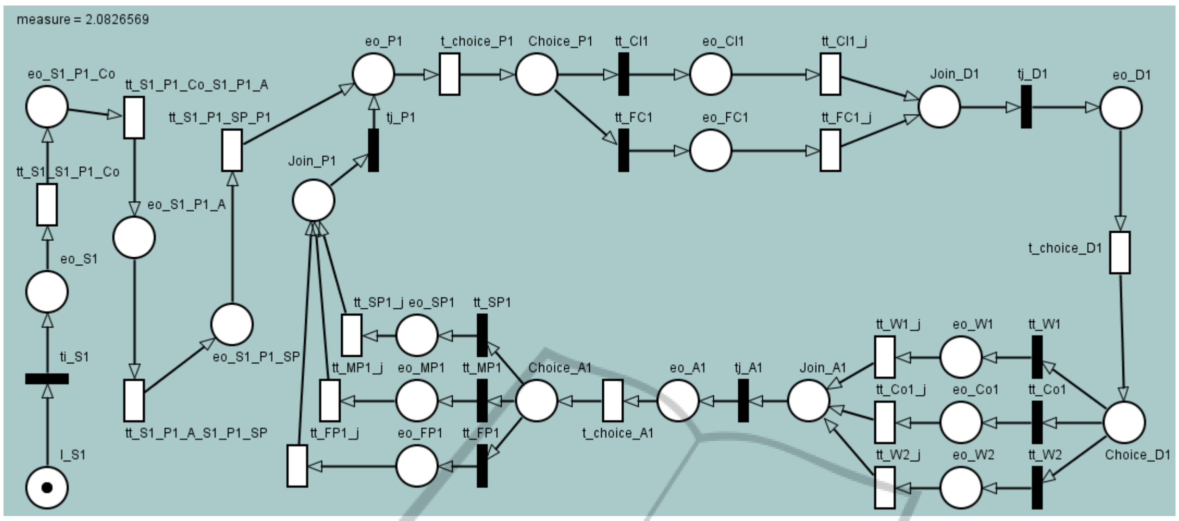


Figure 5: Resulting Petri net of the system.

the most power efficient, statistically it can be used only in 20% of cases. 3 out of 10 units are produced in the middle-speed mode (*MidProd1*), and the half of all orders must be done while using both reserve motors (*FastProd1*). The component is then being packed (*Packaging1*) and the production cycle is here looped. The element *Import* states the XML file containing operational model linked to the current application model. An overview of the attributes given to the states is summarized in the Table 3.

Table 3: Attributes stated in the application model.

State name	execTime, min.	prob
Start1		
Packaging1		
Cleaning1		0.9
FullClean1		0.1
Drying1		
Waiting1	1	0.2
Continue1		0.7
Waiting2	5	0.1
Adaptation1		
SlowProd1		0.2
MidProd1		0.3
FastProd1		0.5

To transform both models into SPN, the user clicks *eSMapp* → *eSMapp to eDSPN*. The information from the application model is being analyzed and the missing data is taken from the operational model. Thus, the power consumption is given only in the operational model. For the states, where execution time is not defined in the application model, this value is also taken from the operational model (e.g. *Start1*, *Packaging1*, *Cleaning1* and so on). Missing states between two similar states are added to make the transition stated in the application model possible (e.g. states *Continue*, *Adaptation* and *SlowProd* are missed between the states *Start1* and *Packaging1*). The parameter *delay* of the exponential transitions is filled up with the information from the attribute *execTime* of the respective simple states. The formula for estimating the power consumption is being filled using the information from the attribute *powerPeak*. The resulting Petri net is shown in Fig. 5.

The stationary analysis of the Petri net results that the power consumption of the system is equal to 2.0826569 Watt.

5 CONCLUSIONS

This paper presented an extension of the software tool TimeNET for model-based estimation of power consumption of embedded systems. The main contribution of the paper is description of two new net classes implemented in TimeNET for modeling the system under consideration. UML extended with several stereotypes of MARTE profile is used for the modeling process. For the modeling part, a system is described with operational and application models, which reflect correspondingly hardware and software parts of the system. These two models are converted automatically into a stochastic Petri net, which is then used for the performance evaluation. The stationary analysis implemented in TimeNET lets the user estimate power consumption of the whole system. The application example an industrial control system, demonstrating that the method is not restricted to microcontroller-based embedded systems.

ACKNOWLEDGEMENTS

The authors would like to thank the Thuringian Ministry of Education, Science and Culture and the German Academic Exchange Service (DAAD) for the financial support of the project. We also recognize the valuable contribution of Andres Canabal Lavista and his student working group to the software tool development.

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