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Obsolescence vs Reliability - Availability - Maintainability: Petri nets modelling for mission-critical systems

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Mission-critical systems like telecommunications networks and defence infrastructures are essential due to their significant role in ensuring security and safety. Maintaining their operational availability is crucial, as any downtime can have serious consequences. While inherent system availability is determined during the design phase, operational availability is influenced by reliability and maintainability, impacted by environmental factors, spare parts, and maintenance resources. Rapid obsolescence of electronic components poses a major risk to operational availability of all systems but far critically for mission-critical systems. This necessitates strategic management to mitigate these risks despite the need for substantial initial investments. This research paper explores the challenge of integrating various types of obsolescence into operational availability using Petri Nets (PN). A physical component within a system's structure is categorised into one of four generically defined classes, based on two criteria that directly affect operational availability: "Make-Buy" and "Repairable-Consumable". Each of these four classes is linked to a specific PN model, called a PN brick, which includes (i) an operational PN, noted $PN_{\lambda\mu}$ and (ii) a set of five PNs that represent potential obsolescence scenarios. The complete model of a mission-critical system is constructed through a top-down analysis of its structure, assigning an appropriate PN brick to each component deemed at risk of obsolescence. This approach allows to model obsolescence interactions with the operational dynamics of (mission-critical) systems by synchronising all the individual PNs. Conclusions and perspectives will conclude the article.

Keywords: Obsolescence, Reliability, Maintainability, Availability, Causality, Petri Nets .

1. Links between Obsolescence and, Reliability, Maintainability, and Availability

Every (complex) system must have a clear mission since 'mission definition is a prerequisite for successful design; it identifies the role the system must play and the results it must achieve to meet the specific needs of a mission' ISO (2015), and since 'the mission of a system forms the basis of design and development. It should include the end goals of the system, ensuring that the system meets the needs of end users and other stakeholders' ISO/IEC/IEEE (2015). A critical system performs its functions in strict compliance with the requirements of its design because its missions involve living people, are of strategic importance, or because they must be performed within a specific time interval or not go beyond a point in time. In

all cases, failure to carry out assignments can have damaging or even uncontrollable consequences (financial, legal, reputational, etc.). Therefore, any mission-critical system must have some of the following characteristics, among others: i) high reliability and availability, ii) ensure data integrity, iii) meet the various security requirements. Obsolescence can have a negative impact on these three characteristics. Difficulties in replenishing components or technologies that have become obsolete can lead to damaging downtime. The obsolescence of an IT protection system against attacks can jeopardise both the integrity of the data and its security. The first objective of the research carried out by authors is to model the mechanisms linking obsolescence to reliability, maintainability and availability. The following objective concerns the possibility of predicting possible degradations in operational availability as a function of obsolescences, whether known or assumed.

In order to estimate this, a series of models were produced using PNs representing the dependencies between obsolescence events and the traditional (real or supposed) breakdown-repair cycle. The choice of Petri nets was notably guided by three points: (i) their ability to simply model processes (nested, concurrent, and parallel) that occur in the functioning of complex systems, (ii) their simplicity to be used as an unambiguous communication formalism easily understandable by industry professionals, while also being enrichable to varying degrees, according to our needs. (iii) Additionally, the use of Petri net models seeks to represent the typical operation of items, particularly through the use of GRaphical Interface for reliability Forecasting (GRIF) to simulate them and derive key indicators of maintainability, reliability, and availability.

The article is structured as follows. The next section provides a brief review of the state of the art, covering the key concepts of obsolescence, reliability, maintainability and availability. The PN models of the components, classified into 4 classes, are then presented and their dependencies are described. Two algorithms are then proposed to define the synchronizations to be implemented in order to model the impact of obsolescence on the availability, maintainability, and reliability of a system. These synchronizations represent the propagation of these impacts within the hierarchical structure of the system. A series of discussions concludes the article by offering directions for future work currently being pursued by the authors.

2. Review of literature

Obsolescence, according to the (IEC 62402, 2019) standard, occurs when a product is no longer available from its manufacturer in accordance with original specifications. It also includes being outdated or losing value, and involve the interruption of supply of essential goods or resources. Obsolescence can be technical, economic, social or skills-related, caused by factors such as technological advances, regulatory changes (such as Restriction of Hazardous Substances (RoHS) or Registration, Evaluation, Authorisation and Restriction of Chemical (REACH)) or changing user needs (Amankwah-Amoah, 2017). These disruptions affect system performance and key parameters such as availability. Availability, which reflects a item's ability to function under specific conditions, can be compromised by disturbances that reduce uptime or increase downtime (NF EN 13306, 2018). It is measured by the ratio uptime / (uptime + downtime) and comprises three categories: inherent, achieved and operational, the latter being the most impacted by delays such as those linked to procurement or maintenance (Stapelberg, 2009). Ensuring the availability of critical systems requires effective maintenance techniques and proactive problem management. Maintainability is essential for preserving availability. It refers to a system's ability to be restored according to defined procedures and resources. It depends on intrinsic factors, such as design characteristics (standardization, interchangeability, accessibility), and extrinsic factors, grouped together under the term "supportability" (spare parts, qualified personnel, documentation) (NF EN 17666, 2022). Disturbances affecting these aspects increase system downtime. Maintainability, fixed at the design stage, involves steps such as access to the faulty component, diagnosis, repair or replacement, and functional validation, influ-

encing the Mean Time to Repair (MTTR), which is directly related to the repair rate μ (Ebeling, 2010). Finally, reliability, measuring the probability of a system performing its function over a given period, is also linked to availability. It is assessed via indicators such as Mean Time To Failure (MTTF) for consumables and Mean Time Between Failures (MTBF) or Mean Operating Time Between Failure (MOTBF) for repairable elements (NF EN 61703, 2017). These indicators are inversely related to the failure rate λ. The failure rate λ and repair rate μ are dynamically adjusted through synchronization with the Petri Net of obsolescence, influencing transition probabilities and durations over time. Obsolescence, reliability, maintainability and availability are intrinsically linked concepts, forming a network of complex interactions that influence system performance. In the following section, we explore these interdependencies through a structured classification, enabling us to analyze the specific dynamics between these concepts.

3. Classification Criteria for Components

A system is a complex entity that can be broken down into several sub-systems, which in turn are made up of more detailed elements that interact with each other. We propose to classify physical constituents of system using two criteria:

(1) Make-or-Buy, $\boldsymbol{M}$ or $\boldsymbol{B}$. It classifies components between those (designed and) manufactured in-house or purchased externally. It determines which actor (the focal company or its supplier) should be involved in solving the obsolescence problem.

(2) Repairable-or-Consumable, $\boldsymbol{r}$ or $\boldsymbol{c}$. This involves determining whether the component is repairable or simply needs to be replaced once its failure (real or perceived) is identified. For repairable components, it is assumed that a percentage of the repaired components will be returned to service, with the remaining components either recycled or used in secondary circuits. A consumable component is replaced; the replaced item is discarded or recycled.

So, the intuition here was to propose a set of four types of components to be able to model any system by assembling these model primitives:

- Make-Repairable, $\boldsymbol{Mr}$. The component is designed and manufactured in-house. The risk of supply interruption is initially low because the entity has ”all” the resources needed to produce the component or, more specifically, to repair the component if necessary. The control of costs and lead times is less complex as it relates to internal resources under the control of the focal company. The same causal reasoning leads to the assumption that downtime will be reduced, thereby maximising operational availability. This is the case, for example, for a train manufacturer that designs and manufactures a repairable braking system. It is plausible to think that the company will be able to control the time and cost of repairing failed modules.
- Buy-Repair, $\boldsymbol{Br}$. This component is bought from a supplier. It may be a component purchased from a catalogue or designed and manufactured to the company’s specifications. The component is repairable. Repairs are carried out by the customer company, the manufacturer or specialist companies. Dependence on external entities for repair and/or supply can lead to additional delays in obsolescence management, which affect operational availability. However, the repairability of the component gives it the same capabilities as Mr.
- Make-consumable, $\boldsymbol{Mc}$. The company designed and manufactured the component; it controls the time and cost of managing obsolescence. Nevertheless, any real or suspected failure of a component means replacement.
- Buy-consumable, $\boldsymbol{Bc}$. The component must be repaired as soon as its failure is considered real or assumed. In this case, which is the most unfavourable a priori in terms of obsolescence management, the component must be restocked from its original supplier and/or approved distributors.

4. States of the system to be considered

A system is modelled from two points of view. The first viewpoint distinguishes at least two states required to define the system's operational availability: 1) Upstate. The item is functional. 2) Downstate. The item is stopped due to an actual or suspected failure, or for preventive maintenance. For the modelling purpose, other states such as degraded can be added to the model if it contributes to the clarification of the run of the system. We also distinguish two states linked to obsolescence, which can affect the components of a system or what are known as contributing entities: with obsolescence and without obsolescence. The obsolescence of one of these elements exposes the system to the risk of unavailability, as it hampers replacement or repair operations (i.e. absence of qualified personnel, documentation, necessary tools and equipment, and know-how at the right time and in the right place). This is clearly likely to automatically lengthen the duration of replacements or repairs, leading to a systematic increase in system unavailability.

5. Operational model of items, i.e. $\lambda\mu$ PN

In this section, we describe the Petri nets that model the operations of each of the four article classes. The description of each Petri net is based on an enumeration of the scenarios taken into account for the modelling. The PN associated with each class is thus a superposition of these scenarios[a]. These PNs only illustrate those situations where all the conditions necessary for carrying out repair or replacement tasks (i.e., availability of personnel, documentation, expertise, and operational consumables) are met. These PN are called $PN_{\lambda\mu}$. The obsolescence of these latter elements are modelled in the PN of the following figures 5.

1) $\lambda\mu$-PN model of a Mc item, Fig.1.

-Scenario 1. After an actual failure, the item enters Downstate, if the quantity is sufficient, the item can be replaced.

-Scenario 2. This is a suspected failure. If it is a false alarm, the item will be back in its initial state.

-Scenario 3. In this case, the alert is indeed true. Replacement should be done if a sufficient quantity of components is available.

$$Pl10 \rightarrow Tr10 \rightarrow (Pl11.Pl13) \rightarrow Tr13 \rightarrow Pl10 \quad (1)$$

$$Pl10 \rightarrow Tr11 \rightarrow Pl12 \rightarrow Tr14 \rightarrow Pl10 \quad (2)$$

$$Pl10 \rightarrow Tr11\ toPl12 \rightarrow Tr12 \rightarrow (Pl11.Pl13) \rightarrow Tr13 \rightarrow Pl10 \quad (3)$$

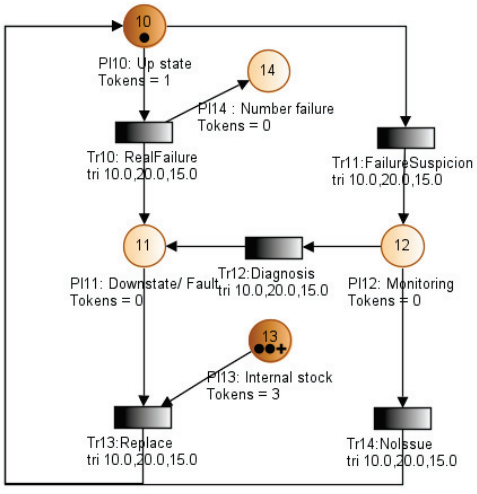

Fig. 1.: $PN_{\lambda\mu}$ model of a Mc item

2) $\lambda\mu$-PN model of a Bc item, Fig.2.

-Scenario 4. Similar to Scenario 1, except for place $Pl23$, which represents external storage; suppliers (external) need to be consulted.

-Scenario 5. Similar to Scenario 2.

-Scenario 6. Similar to Scenario 3 except for $Pl23$.

$$Pl20 \rightarrow Tr20 \rightarrow (Pl21.Pl23) \rightarrow Tr23 \rightarrow Pl20 \quad (4)$$

$$Pl20 \rightarrow Tr21 \rightarrow Pl22 \rightarrow Tr25 \rightarrow Pl20 \quad (5)$$

$$Pl20 \rightarrow Tr21 \rightarrow Pl22 \rightarrow Tr22 \rightarrow (Pl21.Pl23) \rightarrow Tr23 \rightarrow Pl20 \quad (6)$$

3) $\lambda\mu$-PN model of a Mr item, Fig.3.

-Scenario 7. After an actual failure, the item enters Downstate. The item should be then repaired.

-Scenario 8. After an actual failure, the item enters Downstate. If there is a sufficient quantity of components in the internal stock, the item can be replaced.

[a]The character '.' stands for 'AND'

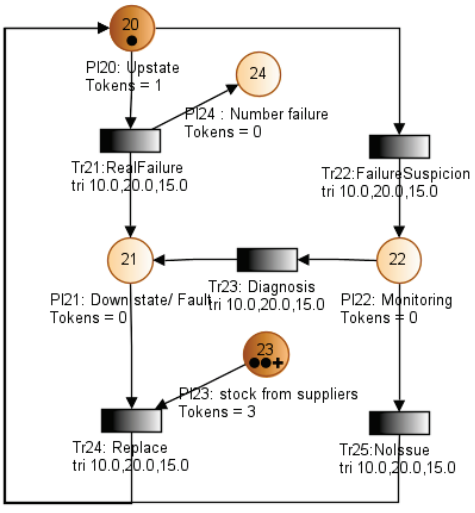

Fig. 2.: $PN_{\lambda\mu}$ model of a $\boldsymbol{Bc}$ item

-Scenario 9. Preventive maintenance is launched as long as there is a sufficient quantity in stock.
-Scenario 10. Following a diagnosis, a replacement is made as long as there is a sufficient quantity in stock.
-Scenario 11. Following a diagnosis, the item is repaired.

$$Pl30 \rightarrow Tr30 \rightarrow Pl31 \rightarrow Tr33 \rightarrow Pl30 \quad (7)$$
$$Pl30 \rightarrow Tr34 \rightarrow Pl31.Pl33 \rightarrow Tr34 \rightarrow Pl30 \quad (8)$$
$$Pl30 \rightarrow Tr31 \rightarrow Pl32.Pl33 \rightarrow Tr35 \rightarrow Pl30 \quad (9)$$
$$Pl30 \rightarrow Tr31 \rightarrow Pl32 \rightarrow Tr32 \rightarrow Pl31.$$
$$Pl33 \rightarrow Tr34 \rightarrow Pl30 \quad (10)$$
$$Pl30 \rightarrow Tr31 \rightarrow Pl32 \rightarrow Tr32 \rightarrow Pl31 \rightarrow Tr33 \rightarrow P130 \quad (11)$$

4) $\lambda\mu$-PN model of a $\boldsymbol{Br}$ item, Fig.4.
-Scenario 12. After an actual failure, the item enters Downstate. The repaired item is re-installed. It is assumed that repairs are under the authority of the supplier.
-Scenario 13. Preventive maintenance is launched as long as the supplier has sufficient stock.
-Scenario 14. Following a diagnosis, a replacement is made if the supplier has sufficient stock.

$$Pl40 \rightarrow Tr40 \rightarrow (Pl41.Pl43) \rightarrow Tr43 \rightarrow Pr40 \quad (12)$$
$$Pl40 \rightarrow Tr4r \rightarrow (Pl42.Pl43) \rightarrow Tr44 \rightarrow Pl40 \quad (13)$$
$$Pl40 \rightarrow Tr41 \rightarrow Pl42 \rightarrow Tr45 \rightarrow Pl41.Pl43 \rightarrow Tr43 \rightarrow Pl40 \quad (14)$$

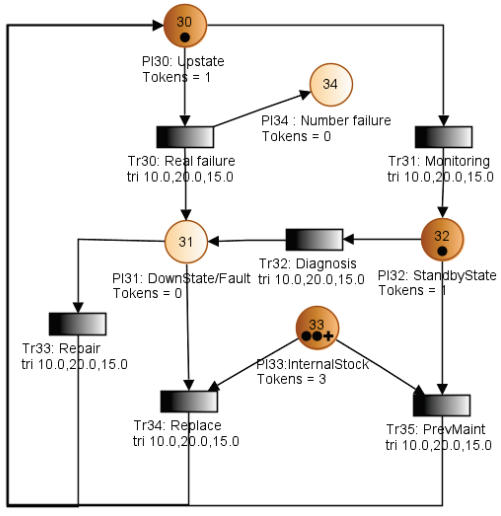

Fig. 3.: $PN_{\lambda\mu}$ model of a $\boldsymbol{Mr}$ item

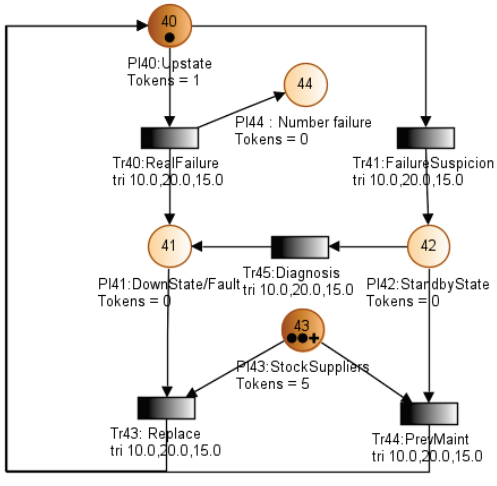

Fig. 4.: $PN_{\lambda\mu}$ model of a $\boldsymbol{Br}$ item

6. Petri Models of Obsolescence

Five PNs are designed to represent the possible obsolescence scenarios considered in this study.

- PN defined to model the item obsolescence, PN_I. This is initially considered as not obsolete by default. This is represented by $Pl100 = 1$. The item becomes obsolete once a Product Discontinuance Notification, PDN in short (or equivalent) is released, $Pl110 =$

1. Solutions must be then identified and implemented. It is supposed that only one solution is adopted each time. At the end of the solution's implementation (e.g. purchase of components), the situation returns to normal.

- The personnel, documentation, operations' consumable components (screws, etc.) and tools PN, noted respectively PN_P, PN_D, PN_C, PN_T. It is considered that initially, personnel, documentation, operations' consumable components and tools are all available and not-obsolete, $Pl200 = Pl300 = Pl400 = pl500 = 1$. If at least one of these entities becomes obsolete then the transitions $Tr200$, $Tr300$, $Tr400$ or $Tr500$ is fired. Solutions must be found for these situations. Once identified and implemented, the situation returns to normal.

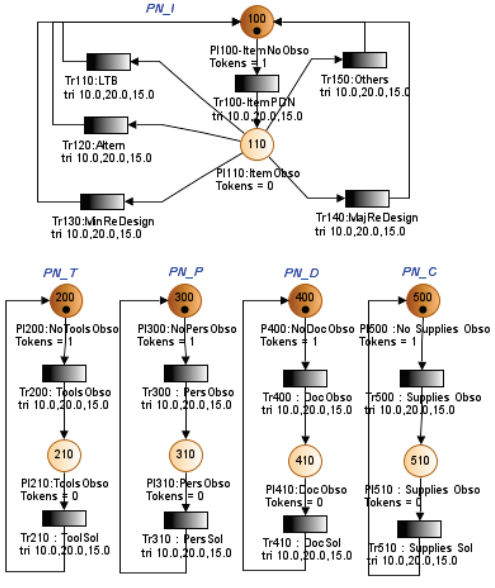

Fig. 5.: Obsolescence PNs

As it was mentioned earlier, the purpose of these Petri nets is to show the situations that need to be addressed. To achieve synchronization, the following procedure must be followed. Indeed, the firing of a transition must adhere to two rules: (i) all upstream places of the transition must be marked (activated), and (ii) all conditions associated with the transition must be validated. These conditions, also called guards, are Boolean equations describing a suitable combination of Boolean variables defined within the network environment. A Boolean variable can represent the state of a place (indicating whether the place holds a token or not), a timing condition, a counting condition, etc. When multiple Petri Nets (PNs) are defined together and intended to represent the operation of a system, it is necessary to define the conditions associated with the transitions to enable process execution. In the following descriptions and algorithms, synchronization will fulfill the following roles: (i) informing the $PN_{\lambda\mu}$s of changes in obsolescence via the places of PN_I, PN_P, PN_D, PN_C, and PN_T, and (ii) informing the $PN_{\lambda\mu}$ of the evolution of obsolescence management via the places of the associated Petri nets. Finally, (iii) synchronization defines the following actions:

- *Modify.* This signifies that the durations of certain operations must be changed. As the principle of these modifications is trivial, it is not defined here.
- *Fill.* This is a command which, following an order emanating from another PN, adds tokens to the places representing stocks. The quantity of tokens to be added depends on the modeling context and is not defined here.

7. Synchronisation of PNs

To clarify the synchronisation principles, cf. Algorithm.1, the example of internal synchronisation between $\{PN_I, PN_P, PN_D, PN_C, PN_T\}$ and $PN_{\lambda\mu}$ of component Mc is used hereafter. The synchronisation of the PNs occurs in the following order (Figure.5):

(1) (a): An obsolescence identified (lines 10 and 11 of the algorithm.1 can change the duration associated with the Tr13 transition. This means that the replacement operations could become longer in presence of obsolescence.

(2) (b): The duration of stay in the Downstate state can lead to the modification of transition durations (i.e. Tr110, Tr120,..., see line 15 of the algorithm.1). This means that it should be possible to accelerate the choice of an obso-

lescence remediation solution.

(3) (c): An obsolescence identified (lines 10 and 11 of the algorithm 1 can change the duration associated with the Tr13 transition.

Algorithm 1 PNs synchronisation: example of MC PNs

1: **Synch1: Guard(Tr13).**
2: **if** $pl100 = pl200 = pl300 = pl400 = pl500 = 1$ **then**
3: Apply the normal rules for firing Tr13.
4: **else if** $pl100 = 0$ **or** $pl200 = 0$ **or** $pl300 = 0$ **or** $pl400 = 0$ **or** $pl500 = 0$ **then**
5: Modify the transition time of Tr13 according to 'Obso-induced rules'.
6: **end if**
7: **Synch2: Guard(Tr10).**
8: **if** $pl100 = pl200 = pl300 = pl400 = pl500 = 1$ **then**
9: Apply the normal rules for firing Tr13.
10: **else if** ($pl100 = 0$ **or** $pl200 = 0$ **or** $pl300 = 0$ **or** $pl400 = 0$ **or** $pl500 = 0$) AND $pl13 = 0$ **then**
11: Modify the transition time of Tr13 according to 'Obso-induced rules'.
12: **end if**
13: **Synch3: Guard of Obso PNs**
14: **if Duration(Pl11)** $>$ **Threshold then**
15: Modify the transition time of ($Tr110$, $Tr120$, $Tr130$, $Tr140$, $Tr150$)
16: **end if**

To enable the calculation of availability in a complex system whose physical structure is defined by a multi-level nomenclature, we establish synchronization principles between PNs within a given level and subsequently between PNs modeling adjacent levels, cf. Algorithm.2.

Synch 1. Within a single component, the duration of transitions leading to shutdown and nominal operating states is modified. These modifications are generated by obsolescence events observed through obsolescence Petri Nets (PNs). These modifications are implemented to account for the probable nature of these impacts.

Synch 2. The duration of transitions leading to shutdown and nominal operating states of component C_3, which depends on another component C_2, is modified. These modifications are generated by obsolescence events observed through the obsolescence PNs of C_2. The primary reason lies in C_3's dependence on data transmission, energy supply, motion transfer, etc., originating from C_2.

Synch 3. The duration of transitions leading to shutdown and nominal operating states of subsystem SS_1, containing components C_1, C_2, C_3, is modified. These modifications are generated by obsolescence events observed through the obsolescence PNs of these components. The primary reason is that the modification of nominal operating and shutdown durations of the subsystem may depend on both the proper functioning and shutdown of these components.

Synch 4. The duration of transitions leading to shutdown and nominal operating states of system S, containing subsystems SS_1, SS_2, SS_3, is modified. These modifications are generated by (1) obsolescence events observed through the obsolescence PNs of subsystems SS_2 and SS_3, (2) duration modifications of SS_1 resulting from synchronization 3. The primary reason for these potential modifications relates to the first-level nomenclature of the system. Thus, the modification of nominal operating and shutdown durations of the system may depend on both the proper functioning and shutdown of the components within these subsystems.

Level 1: The system "Make Repairable" capabilities depend on the performance of its subsystems or components.

Level 2: Subsystems, categorized as Make Repairable, Make Consumable, Buy Repairable, or Buy Consumable, are affected by the obsolescence of their components.

Level 3: Components, always consumables (Make or Buy), are directly impacted by obsolescence, whether of the components themselves or required resources (skills, tools, documentation, personnel).

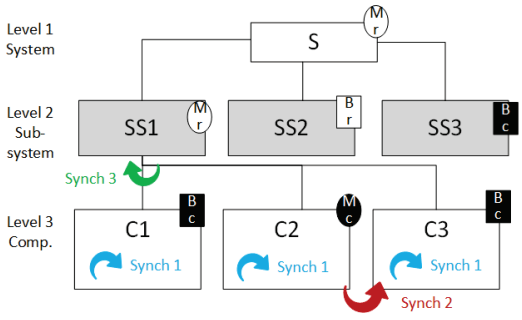

Fig. 6.: Hierarchy of a system

Algorithm 2 Multilevel PNs Synchronisation

1: $i \in \{1, 2, 3\}$
2: **Synch1: Modification of Maint/Reliability duration due to Obso (Level 3, components).**
3: **if** $pl100_i = 0$ **or** $pl200_i = 0$ **or** $pl300_i = 0$ **or** $pl400_i = 0$ **or** $pl500_i = 0$ **then**
4: **Modify** duration $(Diag_i, R/R_i, MaintPrev_i)$
5: **Fill** $Inventory_i$
6: **end if**
7: **Synch2: C3 depends on C2 (Level 3).**
8: **if** ($comp_3$ depends on $comp_2$) **and** ($pl100_2 = 0$ **or** $pl200_2 = 0$ **or** $pl300_2 = 0$ **or** $pl400_2 = 0$ **or** $pl500_2 = 0$) **then**
9: **Modify** duration $(Diag_3, R/R_3, MaintPrev_3)$
10: **end if**
11: **Synch3: Upward propagation (Level 3 to Level 2).**
12: **if duration** $(Diag_i, R/R_i, MaintPrev_i)$**,** $\forall$ **i then**
13: **Modify** duration $(Diag_{SS_1}, R/R_{SS_1}, MaintPrev_{SS_1})$
14: **Fill** $InventorySS_1$
15: **end if**
16: **Synch4: Upward propagation (Level 2 to Level 1).**
17: **if duration** $(Diag_j, R/R_j, MaintPrev_j)$**,** $\forall$ **j then**
18: **Modify** duration $(Diag_S, R/R_S, MaintPrev_S)$
19: **Fill** $Inventory_S$
20: **end if**

8. Conclusions and perspectives

This article focus on mission-critical systems where availability, affected by obsolescence, poses operational challenges. To address this, we identified four product classes and modeled Petri nets for each. These classes influence availability differently, with their rationale explained during classification. For each class, we developed Petri net models representing system operations, including failure states, and incorporating obsolescence effects on items, personnel, documentation, consumables, and tools. We also explored synchronization between Petri nets within entities and their operational models, extending this to a two-level hierarchical system. Two algorithms were proposed to detail the synchronization process step by step. Future work involves implementing these Petri nets in GRIF software for simulations and availability calculations, considering potential obsolescence effects.

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