Fuzzy modelling and robust fault-tolerant scheduling of cooperating forklifts

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***Abstract*—A permanent growth of forklifts' indoor practical applications such as high-storage warehouses makes them dominating transportation tools. It rises the need for their coordinated scheduling including uncertainties related to the human operator behaviour. To tackle this problem, in the paper a novel comprehensive fuzzy logic-based methodology enabling modeling cooperating forklifts and their robust fault-tolerant scheduling is proposed. The advantage of the developed methodology is that it can overcome inevitable conditions like faults, environmental or human-like disturbances and uncertainties. To settle this problem a fuzzy algebraic max plus algebra-based model is proposed and accompanied with a suitable predictive scheduling algorithm. Subsequently, the proposed approach is extended by fault diagnosis mechanisms resulting in a new centrally managed predictive fault-tolerant scheduling system. The efficiency of the proposed approach is evaluated using various simulation scenarios which involve cooperating forklifts transportation tasks operating in a high-storage warehouse of RAFI GmbH & Co. KG company.**

***Index Terms*—Fuzzy systems, fuzzy logic, Takagi-Sugeno model, scheduling algorithms, fault tolerant control, predictive control, max-plus algebra, forklifts**

I. INTRODUCTION

A continuous increasing attention devoted to the Automated Guided Vehicles (AGVs) and Automated Guided Forklifts (AGFs) can be permanently observed [1]–[6]. The high technological development of AGVs and AGFs enables an extension of their application area. Originally, they were mainly used in the transportation systems, ports, reloading terminals and flexible manufacturing systems [4], [5], [7]–[11]. Progressive miniaturization, improvement of electric drives, development of power systems, vision systems, and control systems cause that they are increasingly introduced to new indoor usage areas such as logistic warehouses or logistic centers [12]–[15]. Unfortunately, the application of the AGVs and AGFs is associated with numerous problems and challenges. Among them, the most common issues are related to the optimal route selection, traffic management, avoidance of collisions, deadlocks and congestion. The selection of an optimum number and location of loading and/or unloading places can be also an active research topic [13], [15], [16]. Moreover, the challenges concerning routing, dispatching, scheduling and positioning of idle vehicles can be specified [17]–[19]. Furthermore, the problems connected with the battery management and vehicle failure management also constitute an important research direction [20]. Thus, the newly developed methods should guarantee performance of the whole system, which usually consist of dozens or hundreds of vehicles. During the research, various criteria for different applications can be used. Among them the following can be distinguished: throughput maximization of the transport system, minimization time or cost required to complete all tasks, minimization of maximum or average throughput times of vehicles to achieve the target location.

Despite the incontestable appeal of AGVs and AGFs, the dominant number of forklifts is managed by human operators. In addition, there is a significant number of hybrid transport systems as part of the cooperation of systems combining the use of AGVs and AGFs and human-operated forklifts. Moreover, this number constantly proliferates due to the technological development and the warehouse-based storage behind it. Thus, apart from the above raised application issues, the human-like ones should be included as well:

- How to efficiently model a time-oriented behaviour of a forklift along with human-like uncertainties pertaining its operation?
- How to schedule a fleet of human-operated forklifts performing in a warehouse, including constraints inevitable in their operations?

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Let us start with analysing the first question. Unlike AGFs, human operated forklifts cannot perform a given transportation task precisely in a predefined period of time. Moreover, operator behaviour depends on the work shift length and other factors pertaining human tiredness and other numerous factors [21]. It is also an obvious fact that each human operator has a different performance, which is mostly related to his experience. Thus, the primary goal is to design a model linking operator work efficiency with such factors as: type of transportation task, work experience and current time within the shift. It is an obvious fact that such a model cannot be determined analytically. Thus, fuzzy logic [21]–[31] is a natural modelling paradigm, which can be used to settle this issue. Indeed, it has already proved to be a viable tool for modelling the human work efficiency. Possessing such a model constitutes a necessary condition for answering the second question. Indeed, the partial answer to this question has recently been provided by the authors [32], [33] for a fleet of AGVs. Unfortunately, due to the above listed human operator-like issues, it cannot be directly adapted to the problem being considered. This is due to the fact that the transportation times are assumed constant or contained within given intervals. Nevertheless, Max-Plus Algebra (M-PA) [34]–[36] tools for settling the fleet control and scheduling problem have been proven to be powerful solutions [32], [33]. Thus, the contribution of this paper is to extend the modelling and control paradigm proposed in [32], [33] towards a novel Takagi-Sugeno-based [37] description of the cooperating forklifts managed by human operators.

To solve the above mentioned problem and additionally to fulfill high requirements concerning safety, reliability and availability especially in complex systems consisting of many forklifts, a Fault-Tolerant Control (FTC) [38]–[40] approach is applied. In this place, it should be noted that all variables are used in the proposed system describe times of certain operations. Thus, *a fault* is perceived an unpermitted deviation of a given operation time from its nominal value. The word unperimtted should be interpreted in a fuzzy way and will be carefully explained in the next part of the paper. Finally, a necessary condition for a proper FTC operation is to have Fault Detection and Isolation (FDI) [39]–[44], which is well developed for modern AGVs and AGFs. To cope with the problem of a human-operated forklifts, an innovative SmartSolutions [45] for production efficiency enhancement is employed. It consists of a set of Internet of Things (IoT) tools working in a dedicated environment (see [45] for more details).

In the light of the above discussion, the paper aims at developing an integrated FDI and Model Predictive Control (MPC) [46], [47] technique, which allows to design an effective centrally managed predictive FTC system for a fleet of forklifts. Thus, the main goal of the next section is to deliver a description of the undertaken problem as well as associated research questions, which are answered in the proposed developments. Moreover, the remaining part of the paper is organised as follows: Section II presents the considered problem of a development of a coordinated multiple forklift-based warehouse transportation system. Section III shall provide an introductory example, which provides the main motivations behind and highlights the novelty of the proposed approach. Section IV introduces a mixed Takagi-Sugeno max-plus algebraic model of multiple forklifts. Subsequently, Section V provides its compact form. Section VI extends the proposed approach with a Model Predictive Control (MPC) scheme while Section VII provides new tools for task coordination and fault diagnosis with a concept of SmartSolutions [45]. These tools are further exploited in Section VIII to form a new robust fault-tolerant scheduling framework for multiple forklifts. Finally, Section IX shows a preliminary Proof-of-Concept study concerning a prospective application in RAFI Co. & KG. warehouse.

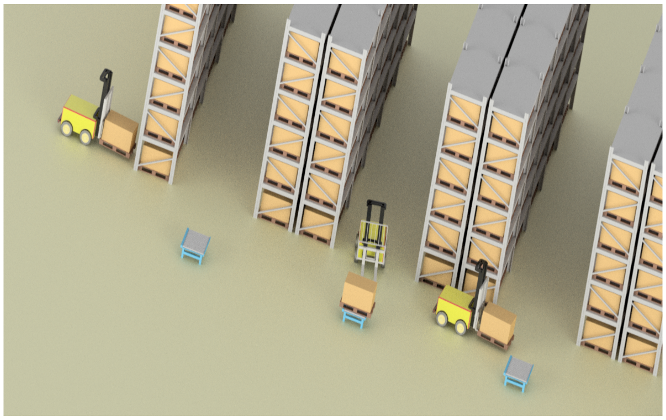

Fig. 1. Forklift-based transportation system

II. Problem overview

Before tackling the issues related with a human forklift operator, let us provide a general problem overview. The problem undertaken in this paper concerns the development of a coordinated multiple forklift-based warehouse transportation system, which is portrayed in Fig. 1. The figure shows an exemplary warehouse which is divided into four main segments. It also portrays three item transfer stations. The main problem is to schedule the work of forklifts, which pertains item transportation from transfer stations towards the designated warehouse segments. For the purpose of further deliberations, each item is defined by a set of features assigned at the level of Manufacturing Execution System (MES):

$$\mathbb{M}(k) = \{p(k), s(k), u_{ref}(k)\}, \tag{1}$$

where:

- k is the item number, i.e. $k = 0, 1, \ldots$;
- $s(k)$ is a storage place number in a warehouse;
- $p(k)$ is a transfer station number;
- $u_{ref}(k)$ is the expected time at which k item arrives to the transfer station $p(k)$;
- $u(k)$ is the transport start time of kth item from the station $p(k)$ towards storage place $s(k)$, which has to be determined.

Note that $u_{ref}(0),\dots,u_{ref}(n_{shift})$ constitute the planned item delivery schedule on transfer stations within one shift, where n_{shift} is the number of items transported within one shift.

Additionally, let us define the following variables:

- n_s and n_v are the numbers of transfer stations and forklifts, respectively;
- $v_i(k)$ (for $i = 1,\dots,n_v$) is a decision variable providing a binary decision on transporting kth item by ith forklift. Note that $v_i(k)$ takes the values from a set $\{e, \varepsilon\}$ where $e = 0$ – positive decision and $\varepsilon = -\infty$ – negative decision.
- $x_i(k)$ is the time when ith forklift ($i = 1,\dots,n_v$) is ready to transport kth item;
- $x_{n_v+1}(k)$ is the kth item release time at $s(k)$ storage point;
- $c(k)$ is the time of collecting and transporting k-th item from $p(k)$ station to $s(k)$ storage place;
- $b(k)$ is the time of item releasing and forklift travel time from $s(k)$ storage place to station $p(k)$.

To complete the description of the entire problem, some essential limitations of the considered system have to be introduced:

Item delivery constraint:

The start time of taking kth item from $p(k)$ transfer station should satisfy the following condition:

$$u_{ref}(k) + d(k) \geq u(k) \geq u_{ref}(k), \qquad (2)$$

where $d(k)$ is a known maximum allowable settle time of kth item at $p(k)$ transfer station. It simply means that the item cannot be collected from the transfer station before it is available at it. While $u_{ref} + d(k)$ signifies the fact that kth item can stay longer that this time at a given transfer station.

Transfer station constraint:

For a given transfer station $p(k)$, kth item should be taken before lth one will arrive. It amounts to the following constraint:

$$\text{IF } p(k) = p(l) \text{ and } l > k, \text{ THEN } u(k) \leq u_{ref}(l). \qquad (3)$$

Feasibility constraint:

The ith forklift can take an item from ith, $i-1$th and $i+1$th transfer station. Note that taking the item from $i-1$th transfer station is possible iff $i \geq 2$. Similarly, taking the item from $i+1$th transfer station is possible iff $i \leq n_s - 1$. This can be expressed as follows:

$$\text{IF } p(k) \in \{i-1, i, i+1\}, \text{ THEN} \qquad (4)$$

$$v_{p(k)}(k) = e, \text{ ELSE } v_{p(k)}(k) = \varepsilon. \qquad (5)$$

Finally, note that MES is a source of a sequence of the items in the following form:

$$\mathbb{M}(0), \mathbb{M}(1), \dots, \mathbb{M}(N_p - 1), \qquad (6)$$

where N_p denotes the transportation horizon. Thus, the main objective is to coordinate the work schedule of n_v forklifts resulting in a sequence of item collecting times:

$$u(0), u(1), \dots, u(N_p - 1). \qquad (7)$$

The efficiency of a forklift transport system is expressed according to the following cost function:

$$J(u) = -\sum_{k=0}^{N_p-1} u(k+j). \qquad (8)$$

The above function has to be minimized under the above-listed constraints. Apart of them a constraint concerning concurrency between multiple forklifts is introduced in the subsequent part of the paper. Indeed, the selection of a forklift (from a set of n_v forklifts) operating on kth item is the crucial point of the developments being proposed. This issue raises another constraint, which should set transportation times to zero for all forklifts that do not transport kth item, whereby the largest possible sum of (7) is achieved. Such a strategy allows the maximum spread between consecutive item presence at transfer stations. To tackle the above-defined problem a list of questions has to be answered:

- How to mathematically describe n_v forklifts allowing an efficient and on-line scheduling of their work?
- How to derive a sequence (7) minimizing (8) under constraint present in the system?
- How to manage possible inconsistencies from the desired behaviour expressed in significant transportation delays and possible constraint violations?

In order to solve the first problem, a novel M-PA based framework is developed. The application of the MPC approach for a set of n_v forklifts can be the solution to the second problem. However, to make the above approach applicable, the model for computing a human operator dependent transportation times $c(k)$ and $b(k)$ has to be developed.

III. INTRODUCTORY EXAMPLE

In this section an introductory example clearly explaining the main ideas of the paper is presented. Let us consider a single forklift, and hence, its time of availability for transport $k-1$th item is denoted by $x_1(k-1)$ while its availability for collecting $x_1(k)$ obeys:

$$x_1(k) = \max(x_1(k-1) + c_1(k-1) + b_1(k-1), u(k)). \qquad (9)$$

Thus, there are two conditions for collecting kth item, i.e. the operator finished transporting kth item (it lasts $c_1(k) + b_1(k)$) and the kth item is available, which is signified by time $u(k)$. Thus, the maximum of the above times is selected as a starting time for collecting kth item, i.e. $x_1(k)$. However, it is an obvious fact that $c_1(k) + b_1(k)$ depends on the experience of the forklift operator. Thus, for calculating reasonable and feasible transportation times $c_1(k)$ and $b_1(k)$, the following linguistic variables are introduced:

- z is the ith forklift operator experience;
- t is the ith forklift operator work time;

while their interpretation is given in Tab. I. It allows formulating a set of rules in the Takagi-Sugeno [48] representation:

$$\begin{aligned} &\text{IF } z \in M_{z,i} \text{ and } t \in M_{t,j}, \text{ THEN} \\ &x_1(k) = \max(x_1(k-1) + c^l + b^l, u(k)). \end{aligned} \qquad (10)$$

TABLE I
LINGUISTIC VARIABLES AND THEIR INTERPRETATION

Linguistic variable	Linguistic values	Intervals
z_i	Beginner	0.0-0.4
	Intermediate	0.3-0.7
	Advanced	0.6-1.0
t_i	Short	0-4
	Medium	3-6
	Long	5-8

where $M_{z,i},\ i=1,\ldots,3$ and $M_{t,j},\ j=1,\ldots,3$ stand for the fuzzy sets associated with variables z and t while c^l+b^l shape the resulting lth submodel. Finally, the model (10) can be expressed in the form (9) where:

$$c_1(k-1)=\sum_{l=1}^{M}\mu_l(t,z)c^l,\ b_1(k-1)=\sum_{l=1}^{M}\mu_l(t,z)b^l, \quad (11)$$

where $\mu_l(t,z)$ $(l=1,\ldots,M)$ signifies the normalised lth rule firing strength which satisfies:

$$\sum_{l=1}^{M}\mu_l(t,z)=1, \quad \mu_l(t,z)\geq 0. \quad (12)$$

The above example and the resulting novel Takagi-Sugeno model of a single forklift performance constitute the preliminary step towards a multiple forklift Takag-Sugeno modelling framework. This is the objective of the subsequent section.

IV. MATHEMATICAL DESCRIPTION OF MULTIPLE FORKLIFTS

Let us start with the generalization of the approach proposed in the preceding section (eq. (11)) which leads to the transformation:

$$c_i(k)=\sum_{l=1}^{M}\mu_l(w)c^l, \quad (13)$$

$$b_i(k)=\sum_{l=1}^{M}\mu_l(w)b^l, \quad (14)$$

$$\sum_{l=1}^{M}\mu_l(w)=1, \quad \mu_l(w)\geq 0. \quad (15)$$

where $\mu_l(w)$ $(l=1,\ldots,M)$ stand for the normalised lth rule firing strength while w denotes a vector of measurable premise variables.

The purpose of the further part of this section is to develop a method for determining real-time scheduling of multiple forklifts for an assumed horizon N_p. It should be underlined that the value $v_i(k)=e$ denotes that ith forklift performs a transportation task of kth item and $v_i(k)=\varepsilon$ means that the forklift is waiting for the transport task to be assigned.

Thus, the trip time of ith forklift, which transport kth item are equal to (13)–(14), and the remaining forklift transportation times are equal to zero:

$$c_i(k)=\sum_{l=1}^{M}\mu_l(w)c^l,\ b_i(k)=\sum_{l=1}^{M}\mu_l(w)b^l, \quad (16)$$

$$c_j(k)=0,\ b_j(k)=0, \quad \forall j\neq i, \quad j=1,\ldots,n_v. \quad (17)$$

Based on the above assumptions the time-evolution of $x_i(k)$ for each forklift can be expressed as:

$$\begin{aligned} x_i(k)=\max(&x_i(k-1)+b_i(k-1)+c_i(k-1),\\ &u(k)+v_i(k)), \quad i=1,\ldots,n_v, \end{aligned} \quad (18)$$

with the related constraints

$$b_i(k)=\max\left(e,\sum_{l=1}^{M}\mu_l(w)b^l+v_i(k)\right), \quad (19)$$

$$c_i(k)=\max\left(e,\sum_{l=1}^{M}\mu_l(w)c^l+v_i(k)\right), \quad (20)$$

and

$$v_i(k)=e \quad \Leftrightarrow \quad v_j(k)=\varepsilon, \quad \forall i\neq j. \quad (21)$$

It should be underlined that (19) corresponds to (16) while (21) expresses the fact that only one ith forklift may transport kth item from the transfer station $p(k)$ towards $s(k)$ storage place. Furthermore, the kth item delivery time at $s(k)$th storage place is defined as follows:

$$\begin{aligned} x_{n_v+1}(k)=\max(&x_1(k)+c_1(k)+v_1(k),\\ &x_2(k)+c_2(k)+v_2(k),\\ &x_3(k)+c_3(k)+v_3(k),\ldots,\\ &x_{n_v}(k)+c_n(k)+v_n(k)\\ &,x_{n_v+1}(k-1)+h(k)), \end{aligned} \quad (22)$$

where $h(k)$ is a time between consecutive $x_{n_v+1}(k-1)$, $x_{n_v+1}(k)$. It is intentionally introduced to model possible system constraints, e.g., forklift settling time between consecutive items. However, if there is no need for such a constraint then it simply reduces to $h(k)=0$.

V. COMPACT FORKLIFT MODEL

This section aims at transforming (18)–(22) into a condensed state-space form. By analysing (18)–(22), one can easily deduce that the only $+$ and $\max$ operators are applied. In such case the max-plus algebra [35], [36], [49] belonging to the class of Discrete Event System (DES) modelling techniques [50], [51] can be used. It is important to emphasise that in its classical form, such approach may be only applied to model a class of DES involving synchronisation but not to concurrency or selection. Such unappealing restriction can be relaxed by the switching max-plus linear system [52]. The approach developed in this work relaxes further the approach [52] by using a set of time-spanned decision variables $\{(v_i(k),v_i(k-1))\}_{k=1}^{N_p}$ instead of a single static one. Let (max,+) be an algebraic structure ($\mathbb{R}_{max}$,$\oplus$,$\otimes$) such that: $\mathbb{R}_{max} \triangleq \mathbb{R} \cup \{-\infty\}$, for all $a, b \in \mathbb{R}_{max}$ where $a \oplus b = \max(a, b)$, for all $a, b \in \mathbb{R}_{max}$ where $a \otimes b = a + b$ with $\mathbb{R}_{max}$ being a real number field. Whilst $\oplus$ and $\otimes$ signify (max,+) addition and multiplication: $\forall a \in \mathbb{R}_{max} : a \oplus \varepsilon = a$ and $a \otimes \varepsilon = \varepsilon$, $\forall a \in \mathbb{R}_{max} : a \otimes e = a$. These operators can be applied to matrices $\boldsymbol{X}, \boldsymbol{Y} \in \mathbb{R}_{\max}^{m \times n}$ and $\boldsymbol{Z} \in \mathbb{R}_{\max}^{n \times p}$:

$$\begin{aligned} (\boldsymbol{X} \oplus \boldsymbol{Y})_{ij} &= x_{ij} \oplus y_{ij} = \max(x_{ij}, y_{ij}), \qquad (23) \\ (\boldsymbol{X} \otimes \boldsymbol{Z})_{ij} &= \bigoplus_{k=1}^{n} x_{ik} \otimes z_{kj} = \max_{k=1,\ldots,n} (x_{ik} + z_{kj}). \end{aligned}$$

For further details the reader is refereed to [34].

On the above assumptions the model (18)–(22) can be redefined as follows:

$$\begin{aligned} x(k) = {} & A(v(k-1), v(k), k) \otimes x(k-1) \\ & \oplus B(v(k), k) \otimes u(k) \end{aligned} \qquad (24)$$

with $\boldsymbol{x}_(k) = [x_1(k), x_2(k), \ldots, x_{n_v}(k), x_{n_v+1}(k)]^T$, and $v(k) = [v_1(k), \ldots, v_{n_v}(k)]^T$, where $\boldsymbol{A}(\cdot, \cdot, \cdot) \in \mathbb{R}_{max}^{n_v+1 \times n_v+1}$ designates $\boldsymbol{x}_k$ transition matrix, while matrix $\boldsymbol{B}(\cdot, \cdot) \in \mathbb{R}_{max}^{n_v+1}$ represents control matrix. Thus, injecting (18) to (22) the following expresion can be defined :

$$\begin{aligned} & x_{n_v+1}(k) = \\ & = \max(x_1(k-1) + b_1(k-1) + c_1(k-1) + c_1(k) + v_1(k), \\ & x_2(k-1) + b_2(k-1) + c_2(k-1) + c_2(k) + v_2(k), \ldots, \\ & x_{n_v}(k-1) + b_{n_v}(k-1) + c_{n_v}(k-1) + c_{n_v}(k) + v_{n_v}(k), \\ & u(k) + c_1(k) + v_1(k), u(k) + c_1(k) + v_2(k), \\ & u(k) + c_3(k) + v_3(k), \ldots, u(k) + c_{n_v}(k) + v_{n_v}(k), \\ & x_{n_v+1}(k-1) + d(k)). \end{aligned} \qquad (25)$$

The combination of expressions (18) and (25) allows obtain $A(v(k-1), v(k), k)$ and $B(v(k), k)$, which are described by relations (26).

The matrices (26) will be expressed by symbols $A_v(k)$ and $B_v(k)$ in the next part of the paper.

VI. MPC OF MULTIPLE FORKLIFTS

This section aims at answering the second question stated in the problem overview section. It deals with finding an optimal sequence (7) minimising (8) for the assumed value of N_p by taking into consideration all problem-oriented and forklift-based constraints. The proposed strategy inherits its core structure from the MPC for max-plus linear systems [49] and extends it by decision variables $v_i(k)$, $v_i(k-1)$ for $i = 1, \ldots n_v$. Let us recall that the input sequence $u(k), \ldots, u(k+N_p-1)$ on a moving horizon $k, \ldots, k+N_p-1$ should be selected as:

$$J(y) = -\sum_{j=0}^{N_p-1} u(k+j). \qquad (27)$$

This means that values $u(k), \ldots, u(k+N_p-1)$ have to be determined for each k. On the beging a prediction rule of $\boldsymbol{x}_(k+1), \ldots, \boldsymbol{x}_(k+N_p-1)$ should be defined:

$$\tilde{u}(k) = \begin{bmatrix} u(k) \\ u(k+1) \\ \vdots \\ u(k+N_p-1) \end{bmatrix}, \ \tilde{x}(k) = \begin{bmatrix} x(k) \\ x(k+1) \\ \vdots \\ x(k+N_p-1) \end{bmatrix},$$

and

$$\tilde{v}(k) = \begin{bmatrix} v(k) \\ v(k+1) \\ \vdots \\ v(k+N_p-1) \end{bmatrix}, \ v(k) = [v_1(k), \ldots, v_{n_v}(k)]^T. \qquad (28)$$

Finally, a recursive application of (24) yields:

$$\tilde{x}(k) = \boldsymbol{M}(\tilde{v}(k)) \otimes x(k-1) \oplus \boldsymbol{H}(\tilde{v}(k)) \otimes \tilde{u}(k), \qquad (29)$$

with

$$\boldsymbol{H}(\tilde{v}(k)) = \begin{bmatrix} \boldsymbol{H}_{11}(\tilde{v}(k)) & \cdots & \boldsymbol{H}_{1N_p-1}(\tilde{v}(k)) \\ \boldsymbol{H}_{21}(\tilde{v}(k)) & \cdots & \boldsymbol{H}_{2N_p-1}(\tilde{v}(k)) \\ \vdots & \ddots & \vdots \\ \boldsymbol{H}_{N_p-11}(\tilde{v}(k)) & \cdots & \boldsymbol{H}_{N_p-1N_p-1}(\tilde{v}(k)) \end{bmatrix},$$

$$\boldsymbol{M}(\tilde{v}(k)) = \begin{bmatrix} \boldsymbol{M}_1(\tilde{v}(k)) \\ \boldsymbol{M}_2(\tilde{v}(k)) \\ \vdots \\ \boldsymbol{M}_{N_p}(\tilde{v}(k)) \end{bmatrix}, \qquad (30)$$

where:

$$\begin{aligned} \boldsymbol{M}_n(\tilde{v}(k)) = {} & \boldsymbol{A}_v(k+n-1) \otimes \boldsymbol{A}_v(k+n-2) \otimes \\ & \ldots \otimes \boldsymbol{A}_v(k), \end{aligned} \qquad (31)$$

and

$$\boldsymbol{H}_{nm}(\tilde{v}(k)) = \begin{cases} \boldsymbol{A}_v(\cdot, \cdot, k+n-1) \otimes & \ldots \\ \otimes \boldsymbol{A}_v(\cdot, \cdot, k+m) & \\ \otimes \boldsymbol{B}_v(k+m-1) & \text{if } n > m \\ \boldsymbol{B}_v(\cdot, k+n-1) & \text{if } n = m \\ \epsilon & \text{if } n < m \end{cases} \qquad (32)$$

Subsequently, a set of constraints (2)–(5) required during repetitive optimization cycles on $k \ldots, k+N_p-1$ should be taken into consideration:

Transportation: expressed by (19)–(20) pertains transportation times of a set of forklifts:

$$b_i(k) = \max\left(e, \sum_{l=1}^{M} \mu_l(w) b^l + v_i(k)\right), \qquad (33)$$

$$c_i(k) = \max\left(e, \sum_{l=1}^{M} \mu_l(w) c^l + v_i(k)\right). \qquad (34)$$

Concurrency: expressed by (21) concerns selecting forklift transporting k-th item:

$$v_i(k) = e \quad \Leftrightarrow \quad v_j(k) = \varepsilon, \quad \forall i \neq j. \qquad (35)$$

$$\begin{aligned} A(v(k-1),v(k),k) &= \begin{bmatrix} b_1(k-1)+c_1(k-1) & \varepsilon & \dots & \varepsilon \\ \varepsilon & b_2(k-1)+c_2(k-1) & \dots & \varepsilon \\ \vdots & \vdots & \ddots & \vdots \\ b_1(k-1)+c_1(k-1)+c_1(k)+v_1(k) & b_2(k-1)+c_2(k-1)+c_2(k)+v_2(k) & \dots & h(k) \end{bmatrix}, \\ B(v(k),k) &= \left[v_1(k), v_2(k), \dots, v_{n_v}(k), \max(c_1(k)+v_1(k), \dots, c_{n_v}(k)+v_{n_v}(k))\right]^T . \end{aligned} \tag{26}$$

For the purpose of brevity let us denote all constraints (2)–(5) and (33)–(35) concerning operations for kth item by a set $\mathbb{C}(k)$. Finally, the optimization problem reduces to:

$$(\tilde{u}(k)^*, \tilde{v}(k)^*) = \arg \min_{\tilde{u}(k),\tilde{v}(k)} J(u), \tag{36}$$

under $\mathbb{C}(k), \dots, \mathbb{C}(k+N_p-1)$. Having a formal description of the optimization problem, an MPC algorithm 1 for multiple forklifts can be formulated:

Algorithm 1: Multiple forklifts max-plus MPC

```
Step 0:
    For $k = 1$ assume $v(0)$ and $N_p$.
Step 1:
    Receive sequence of $\mathbb{M}(k), \dots, \mathbb{M}(k+N_p-1)$
    from MES.
Step 2:
    Determine the vector of premise variables $w$.
Step 3:
    Build a constraint sequence
    $\mathbb{C}(k), \dots, \mathbb{C}(k+N_p-1)$.
Step 4:
    Obtain state measurement $x^m(k-1)$ and $\tilde{u}(k)^*$
    and $\tilde{v}(k)^*$ resulting from (36) under
    $\mathbb{C}(k), \dots, \mathbb{C}(k+N_p-1)$.
Step 5:
    Take $u(k)^*$ and $u(k)^*$ and apply them for (18).
Step 6:
    Assume $k = k+1$ and go to Step 1.
```

VII. TASK COORDINATION AND FAULT DIAGNOSIS WITH SMARTSOLUTIONS

The crucial task in implementing the control strategy proposed in the preceding section is to have an infrastructure capable of measuring actual operation times, i.e. $b_i(k)^m$, $c_i(k)^m$ performed by ith forklift operator. To tackle this problem, SmartSolutions [45] technology concept is employed. It consists of a set of IoT being interconnected signal lamps and pushbutton boxes (see Fig. 2), which make the transportation process transparent and measurable. Both lights and pushbuttons (their rings around buttons) can light with any RGB colour, which can be remotely changed.

Fig. 2. SmartSolutions IoT [45]

Having such a solution, let us start with providing a practical implementation of the scheme presented in Fig. 3. Thus, each transfer station is equipped with the signal lamp lighting in a different colour while each forklift is equipped with a push button. Note that the green and red colours are reserved for the operational purposes. The above couple of IoT tools will indicate the operator how to perform transportation. It is achieved in the following steps:

Step 1: The transfer station $p(k)$ lamp lights with a colour **X** (**blue** in Fig. 3).

Step 2: The designated forklift push button rings light with a colour **X** (**blue** in Fig. 3)

Step 3: The operator pushes first button and its ring starts to light in a red colour. From that moment, the measurement of time $c_i(k)^m$ begins and the operator starts collecting and transferring kth item from the station $p(k)$ to the storage place $s(k)$.

Step 4: The operator accomplishes transportation of kth item and pushes first button. Its ring starts to light in a green colour. The measurement of $c_i(k)^m$ ends.

Step 5: The operator pushes second button and its ring starts to light in a red colour. From that moment, the measurement of time $b_i(k)^m$ starts and the operator begins releasing kth item at $s(k)$ storage place and then goes to $p(k)$.

Step 6: The operator arrives at $p(k)$ and pushes the second button. Its ring starts to light in a green colour. The measurement of $b_i(k)^m$ ends and full transport cycle is accomplished.

Having the measurements of $c_i(k)^m$ and $b_i(k)^m$ it is possible to compare them with its nominal values. The transportation behind schedule for which the measured route times $b_i(k)^m$ and $c_i(k)^m$ are not smaller than $c_i(k)$ and $b_i(k)$ are

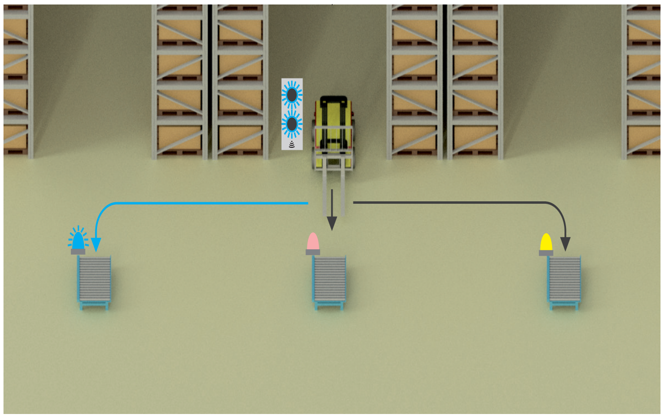

Fig. 3. Forklift transportation options

assumed as *faults*:

$$\begin{aligned}
&\text{IF } c_i(k)^m \le c_i(k), \text{ THEN } f_{i,c}(k) = 0,\\
&\text{ELSE } f_{i,c}(k) = c_i(k)^m - c_i(k),\\
&\text{and} \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad (37)\\
&\text{IF } b_i(k)^m \le b_i(k), \text{ THEN } f_{i,b}(k) = 0,\\
&\text{ELSE } f_{i,b}(k) = b_i(k)^m - b_i(k). \qquad\qquad (38)
\end{aligned}$$

VIII. FAULT-TOLERANT FORKLIFT SCHEDULING

This section answers the third question stated in the problem overview section. It proposes a solution for the accommodation of potential faults defined by (37).

As a result of faults (37) the transfer station constraint (3) could be violated. It means that kth item will still stand at the transfer station $p(k)$ while lth one ($l > k$) will arrive. One way to settle such problem is to introduce a time varying relaxation factor $\alpha(l) \ge 0$ to expression (39):

$$\begin{aligned}
&\text{IF } p(k) = p(l) \text{ and } l > k, \text{ THEN}\\
&u(k) \le u_{ref}(l) + \alpha(l)
\end{aligned} \tag{39}$$

which signifies a necessary delay in delivering lth item to $p(l)$ transfer station. It denotes that the original set of constraints $\mathbb{C}(k)$ has to be updated by replacing (3) with (39). The cost related to introducing $\alpha(k)$ can be expressed by:

$$J(\alpha) = \sum_{j=0}^{N_p-1} \alpha(k+j), \tag{40}$$

and now an another FTC cost function can be introduced:

$$J(u,\alpha) = (1-\tau)J(u) + \tau J(\alpha), \tag{41}$$

with $0 \le \tau \le 1$. By assuming $\tilde{\alpha}(k) = [\alpha(k), \ldots, \alpha(k+N_p-1)]^T$, the optimization task is rewritten to the following form:

$$(\tilde{u}(k)^*, \tilde{v}(k)^*) = \arg \min_{\tilde{u}(k), \tilde{v}(k), \tilde{\alpha}(k)} J(u,\alpha), \tag{42}$$

under $\mathbb{C}(k), \ldots, \mathbb{C}(k+N_p-1)$. The complete FTC algorithm has also to update $A_v(\cdot,\cdot,\cdot)$ and $B_v(\cdot,\cdot)$ according to fault estimates, which can be arranged as follows with Algorithm 2.

Algorithm 2: Multiple forklifts FTC

```
Step 0:
    For $k = 1$ assume $v(0)$ and $N_p$.
Step 1:
    Receive sequence of $\mathbb{M}(k), \ldots, \mathbb{M}(k+N_p-1)$
    from MES.
Step 2:
    Determine the vector of premise variables $w$.
Step 3:
    For an index $i$ of the forklift transporting $k-1$th
    item corresponding to $v_i(k-1) = e$, $i = 1, \ldots, n_v$,
    measure $x(k-1)$ and values of $b_i(k-1)^m$ and
    $c_i^m(k-1)$ representing the transportation times.
Step 4:
    Obtain the faults with (37) and set up their
    predictors $\hat{f}_{i,b} = f_{i,b}(k-1)$ and $\hat{f}_{i,c} = f_{i,c}(k-1)$.
Step 5:
    If $\hat{f}_{i,b} \neq 0$ and / or $\hat{f}_{i,b} \neq 0$, update $A(\cdot,\cdot,\cdot)$ in
    (26), matching the state $x_i$ of $i$-th forklift:
        $A_{v,i,i}(\cdot,\cdot,\cdot)_{i,i} = b_i(k-1) + c_i(k-1) +$
        $+ \hat{f}_{i,b} + \hat{f}_{i,c},$                                      (43)
        $A_{v,n_v+1,i}(\cdot,\cdot,\cdot) = b_i(k-1) + c_i(k-1) +$
        $+ c_i(k) + \hat{f}_{i,b} + \hat{f}_{i,c} + \hat{f}_{i,c} + v_i(k),$    (44)
    and:
        $b_i(k) = \max\left(e, \sum_{l=1}^{M} \mu_l(w) b^l + \hat{f}_{i,b} + v_i(k)\right),$   (45)
        $c_i(k) = \max\left(e, \sum_{l=1}^{M} \mu_l(w) c^l + \hat{f}_{i,c} + v_i(k)\right).$   (46)
    If $\hat{f}_{i,b} \neq 0$, then:
        $B_{v,n_v+1}(\cdot,\cdot) = b_v(k)$                                    (47)
    whereas
        $b_v(k) = \max(c_1(k) + v_1(k), \ldots, c_{n_v}(k)$
        $+ v_{n_v}(k)).$                                                     (48)
Step 6:
    Build $\mathbb{C}(k), \ldots, \mathbb{C}(k+N_p-1)$.
Step 7:
    Obtain $\tilde{v}(k)^*$ $\tilde{u}(k)^*$ by solving (42)
    $\mathbb{C}(k), \ldots, \mathbb{C}(k+N_p-1)$.
Step 8:
    Take $u(k)^*$ and $v(k)^*$ and apply them for (18).
Step 9:
    For $k = k+1$ go to Step 1.
```

IX. PERFORMANCE EVALUATION

The considered scenario is illustrated in Fig. 1 constitutes a preliminary step towards real conditions at RAFI GmbH Co. & KG. It corresponds to the selected part of warehouse which is presented in Fig. 4 along with in-front transfer stations. This part is operated by $n_v = 3$ forklifts portrayed in Fig. 5.

Fig. 4. RAFI GmbH Co. & KG warehouse

Fig. 5. Exemplary forklift operating within RAFI GmbH Co. & KG warehouse

Let us start with modelling driver behaviour using (13)–(14), i.e.:

$$c_i(k) = \sum_{l=1}^{M} \mu_l(w) c^l, \tag{49}$$

$$b_i(k) = \sum_{l=1}^{M} \mu_l(w) b^l, \tag{50}$$

$$\sum_{l=1}^{M} \mu_l(w) = 1, \quad \mu_l(w) \geq 0. \tag{51}$$

For that purpose drivers with possibly diverse experience should be selected and premise variables vector should be defined as follows:

$$w = [z, t, d(k)]^T, \tag{52}$$

where z and t stand for the driver experience and work time defined in Tab. I, $d(k)$ is the distance between $p(k)$ transfer station and $s(k)$ storage point. This variable has 10 linguistic values $d_1, \ldots, d_{10}$, which correspond to the intervals covering 200 [m] distance of the warehouse. 1-10, 8-20, 18-30, etc. Due to safety purposes the maximum forklift velocities are limited to 5km/h. Thus, the beginner, intermediate and experienced drivers accomplish a given travel distance in a comparable time. The main differences were observed during item collecting and releasing phases because they are correlated to z and t. For the purpose of modelling each fuzzy set was accompanied with a triangular membership function founded at the beginning and the end of the respective intervals (cf. Tab. I) whilst the vertices of each triangle are associated with the centres of these intervals. The identification of parameters c_l and b_l in (49)–(50) was performed with the time measurements provided by the approach detailed in Section VII and the usual least square. For that purpose the data representing different driver experience z and work tiredness t were generated.

Firstly, to make illustrative comparison *Algorithm 1* was run for the fault-free conditions. MES provides information about expected time of item on a given transfer station along with a signature of this transfer station:

$$u_{ref}(k) = \{5, 8, 12, 16, 17, 19, 23, 25, 29\}, \tag{53}$$

$$p(k) = \{1, 2, 1, 3, 2, 1, 2, 2, 1\}. \tag{54}$$

Figure 6 shows fault-free Gantt diagram for MPC (top) and FTC (bottom). This diagram represents schedule of forklifts while applying either *Algorithm 1* or *Algorithm 2* which work exactly the same for both approaches. The second scenario describes the situation with a delay of 2nd forklift during the second phase of transportation. It was caused by an operator fatigue. Because of this, transportation time was longer by 5 minutes:

$$f_{2,c}(k) = \begin{cases} 0 & k < 6 \\ 5 & \text{otherwise.} \end{cases} \tag{55}$$

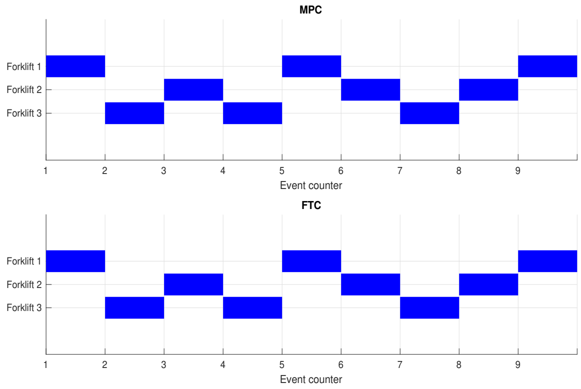

Fig. 6. Gantt diagrams for the fault-free case

The associated Gantt diagrams are portrayed in Fig. 7. It should be underlined that the fault affects both control strategies for $k \geq 6$. Unlike MPC, FTC detects and identifies this delay (6th item) and then performs appropriate accommodation actions. Fig. 8 shows collecting times $x_i(k)$ while i signifies the forklift number carrying kth item, which can be easily determined in Fig. 7.

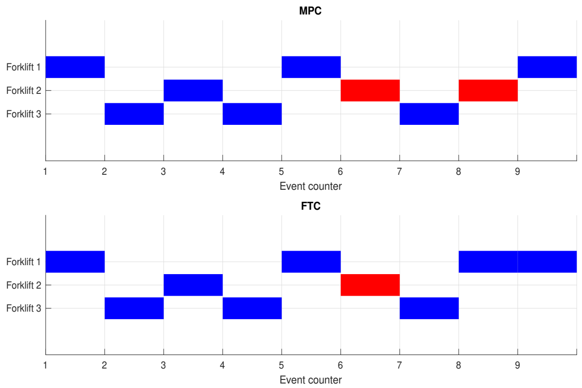

Fig. 7. Gantt diagrams for the faulty case

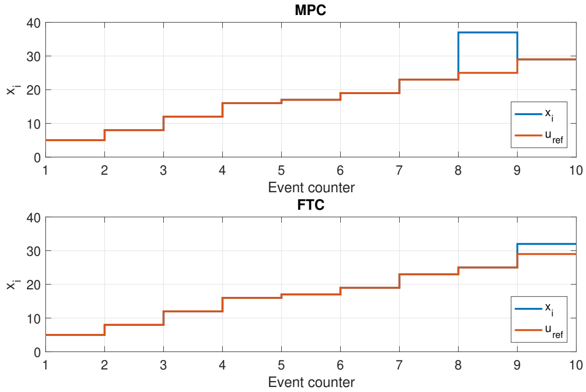

Fig. 8. Item transportation start times

In this scenario, the difference between MPC and FTC can be easily observed. Indeed, MPC cannot counteract this fault because of lack of fault diagnosis and accommodation mechanisms. This causes that MPC selects 2nd forklift, which suffers from a fault, for transferring 8th item. It leads to a significant delay, which is presented in Fig. 8 (top). Unlike MPC, FTC detects the fault and accommodates it actively by employing 1st forklift for transferring 8th item. It is associated with the cost of delaying the start time of transferring 9th item but the overall delay is significantly smaller.

X. CONCLUSIONS

The primary goal of this paper was to develop a unified FTC guaranteeing an optimal allocation of transportation tasks among a set of forklifts both in fault-free and faulty conditions. In particular, the Takagi-Sugeno model of multiple forklifts allowing their future predictions was proposed. As a result, the core MPC framework was extended with concurrency- and FTC related features. The vital advantage of the proposed approach is the fact that the considered cost function is linear in contrast to the quadratic function usually used in this type of tasks. Such feature allows to apply the developed framework in an on-line mode for a real-life scheduling of cooperating forklifts.

The future research will focus on adapting the developed methodology to robust fault-tolerant scheduling of the Automated Guided Vehicles (AGVs). In such case a proposed fuzzy logic-based methodology may take into account state-of-charge and state-of-health of AGVs accumulators as well as some remaining useful life parameters of an AGV, e.g. vibrations on the wheels associated with the degradation of their bearings.

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