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MPC Approach for Synchronized Supply Chains of Perishable Goods

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Abstract—The movement of perishable goods is growing worldwide. Perishable goods need to be available to the market before the expiration date. With the decrease in inventory levels the components of a supply chain become even more integrated and dependent on coordinated decisions. Information regarding perishable goods must be visible throughout the supply chain for avoiding goods loss. A Model Predictive Control (MPC) heuristic to address operations management at supply chains of perishable goods is proposed in this paper. The approach is capable to follow the remaining time until expiration date which is critical to avoid losses. The supply chain is modeled using a state-space representation and operations management at the supply chain is formulated as an MPC Problem. In order to cope with operational decisions, the problem is solved on a periodic basis. The proposed approach is capable to deal with production decisions, monitor work-in-progress (WIP), and make transport assignments while monitoring the remaining time until the expiration date. Flows over the supply chain can be synchronized and therefore we named this type of supply chain a Synchronized Supply Chain (SSC). The approach is modular and easily scalable for large-scale supply chains. Numerical results illustrate these statements.

I. INTRODUCTION

In supply chains (SC) multiple partners (suppliers, manufacturers, retailers) are contributing to move commodities from a source node to a destination node [1]. The challenges posed to operations management at supply chains are increasing in complexity with the spatial distribution of the network. These challenge increase when the value of goods is limited on time, such is the case when dealing with perishable. Moving these goods wisely is critical to assure they are delivered at the right location on the agreed time and quantity in order to be able to collect a revenue.

Supply chains can be found in different domains such as food [2], [3], distribution and retail. A supply chain can move a single commodity or multiple commodities. Commodities can be categorized in two different classes:

- Time-Constant Classes: such as the type of goods (fruit, milk, meat, fish,...), the volume (type of container, individual box,...), the final client location, the client priority, the weight, the temperature of transport;

- Time-Varying Classes: related to the available time to deliver the goods such that a revenue can be received, for instance the expiration date.

A distinction between raw materials (products without an expiration date) and perishable goods (products with an expiration date associated with) is made in this paper. Examples of perishable goods are: different types of fruits, yoghurt, fresh milk, fresh meat and fresh fish. In the case of perishable goods, the economic value of the product is limited in time which means that it has to be transported and delivered where needed respecting its expiration date. Also in some domains, the delivery of cargo should respect a pre-defined time window, which has to be fulfilled or contractual penalties will be triggered. In either case, operations management should track the remaining time until due time to proceed with decision or update decisions in case of need. It is important that information exchange happens throughout the supply chain and that the remaining time to deliver perishable goods is transparent for the different partners. In current supply chain management approaches the available time to deliver cargo is not taken into account [4], [5].

In this paper an MPC Heuristic is proposed to cope with operations management for synchronized supply chains of perishable goods making use of integrated modeling and control techniques, starting in the design phase. In this paper, market demand is interpreted as an exogenous input that disturbs the inventory levels across the supply chain state. Operations management is required to assign flows between nodes such that demand is satisfied without loosing the good value. Model Predictive Control (MPC) has shown to be successfully applied in process industry applications [6], and is now gaining increasing attention in fields like supply chains [7], power

networks [8], and water distribution networks [9]. By using mathematical models to describe the flows inside supply chains it is possible to make predictions about their future behavior. In supply chains, costs can be associated to flows and quantities of stored commodities. The model predictive controller can determine which actions have to be chosen in order to obtain the best performance taking into account the desired goals, existing constraints, disturbances and prediction information if available.

This paper is organized as follows. In Section II the modeling of supply chains is addressed using a state-space approach. Operations management is formulated and addressed using an MPC Heuristic in Section III. The performance of the proposed approach is tested through numerical simulations in Section IV. In Section V conclusions are drawn and future research topics are indicated.

II. MODELING

A. Conceptual Approach

*1) Supply Chain:* At a macroscopic level a supply chain exhibits two major phenomena [10]:

- Potential: related to the storage capability in well-defined areas, where commodities can be produced, manufactured or simply stored. These locations are modelled as *center nodes*, and are used to capture source nodes, intermediate nodes or downstream nodes (see Fig. 1(a));

- Flow: related to the transport or production delay. In this paper, this is modelled using a connection, which is composed of a succession of nodes with an in-degree and out-degree equal to one. Connection j is composed of n_{c_j} nodes and $n_{c_j} + 1$ flows (see Figure 1(b)).

In this paper, the production is not restricted to industrial manufacturing, meaning that if some features of a good have been changed that creates a new good. All supply chains are generally composed of center nodes and connections.

2) Commodities: This paper assumes that commodities in supply chains are categorized in two categories:

- raw materials: n_m is the amount of raw materials in the supply chain (e.g., clothes, package, bottles) which can be measured in units, volume or weight;

- perishable goods: n_g is the number of perishable goods in the supply chain (e.g., pears, pineapple, bananas). Moreover for each perishable good the remaining time until due time is considered via, n_{dt_p}, the number of time steps until due time of perishable good p, typically measured in days. This property is used to consider either the expiration date of perishable cargo or the agreed delivery time. For the sake of readability, from now on this property will be mentioned as due time.

The number of commodities in the supply chain is given by $n_c = n_m + n_g$. The number of properties to track over time
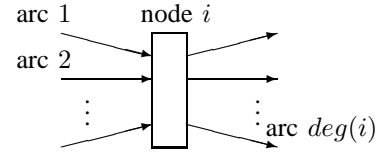
(a) Center node of store type.
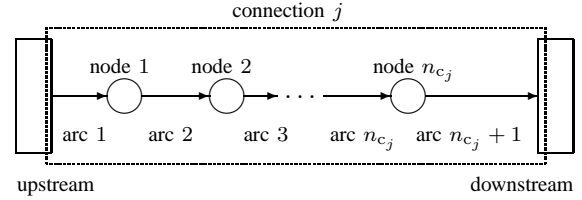
(b) Connection between two center nodes.

Fig. 1. Elementary components in a supply chain ($deg(i)$ stands for node degree).

is given by the contributions of raw materials and perishable goods due time, i.e.,

$$n_p = n_m + \sum_{i=1}^{n_g} n_{dt_i}. \tag{1}$$

B. Supply Chain Model

The total number of nodes inside the supply chain is associated with the topology and is given by

$$n_y = n_n + \sum_{j=1}^{n_c} n_{c_j}, \tag{2}$$

where n_n is the number of center nodes and n_{c_j} is the number of nodes belonging exclusively to connection j. For each node in the supply chain a state-space vector $\bar{\mathbf{x}}_i(k)$, $i = 1, \ldots, n_y$ is defined, and these are merged to form the state-space vector $\mathbf{x}$ of the complete supply chain,

$$\bar{\mathbf{x}}_i(k) = \begin{bmatrix} x_i^1(k) \\ x_i^2(k) \\ \vdots \\ x_i^{n_m}(k) \\ x_i^{1,1}(k) \\ \vdots \\ x_i^{1,n_{dt_1}}(k) \\ \vdots \\ x_i^{n_g,1}(k) \\ \vdots \\ x_i^{n_g,n_{dt,g}}(k) \end{bmatrix}, \mathbf{x}(k) = \begin{bmatrix} \bar{\mathbf{x}}_1(k) \\ \bar{\mathbf{x}}_2(k) \\ \vdots \\ \bar{\mathbf{x}}_{n_y}(k) \end{bmatrix}, \tag{3}$$

where $x_i^{p,dt_p}(k)$ is the amount of perishable good p with the maximum due time dt_p at node i at time step k, and $n_{dt,g} = n_{dt_{n_g}}$ is the number of due times for time a given good n_g. The state-space dimension is given by $n_x = n_y n_p$ corresponding to the number of properties handled and the

number of nodes existing in the supply chain. For the case of considering only raw materials, $n_{dt_p} = 1$, what reduces to $n_x = n_y n_c$. The state-space vector contains information about the amount per commodity not only at the center nodes, with significant storage capacity, but also at flow nodes. The total amount per commodity inside the supply chain is always accessible through the state-space vector: either in storage, transport or work-in-progress (WIP).

The demand is seen as an exogenous input $\mathbf{d}$ with length $n_d = n_c$. This means that the remaining due time is not tracked at the retail shop, and it is assumed that a FIFO policy is used at the retail shop shelves. Consider $u_j^{p,dt_p}(k)$ as the amount of commodity p and due time dt_p to be pulled from node j at time step k. For all admissible flows inside the Supply Chain a control action vector is defined $\bar{\mathbf{u}}_j$ with length n_p. All $\bar{\mathbf{u}}_j$ ($j = 1, \ldots, n_f$), where n_f is the number of available flows, are merged to form the overall control action vector $\mathbf{u}(k)$ with length $n_u = n_f n_p$:

$$\bar{\mathbf{u}}_j(k) = \begin{bmatrix} u_j^1(k) \\ u_j^2(k) \\ \vdots \\ u_j^{n_m}(k) \\ u_j^{1,1}(k) \\ \vdots \\ u_j^{1,n_{dt,1}}(k) \\ \vdots \\ u_j^{n_g,1}(k) \\ \vdots \\ u_j^{n_g,n_{dt,g}}(k) \end{bmatrix}, \mathbf{u}(k) = \begin{bmatrix} \bar{\mathbf{u}}_1(k) \\ \bar{\mathbf{u}}_2(k) \\ \vdots \\ \bar{\mathbf{u}}_{n_f}(k) \end{bmatrix}. \quad (4)$$

The model for the supply chain can then be represented in a state-space form as

$$\mathbf{x}(k+1) = \mathbf{A}\mathbf{x}(k) + \mathbf{B}_u\mathbf{u}(k) + \mathbf{B}_d\mathbf{d}(k), \quad (5)$$
$$\mathbf{y}(k) = \mathbf{x}(k), \quad (6)$$
$$\mathbf{x}(k) \geq \mathbf{0}, \quad (7)$$

where $\mathbf{y}$ is the current amount per commodity at all nodes with dimension $n_y = n_x$, $\mathbf{A}$, $\mathbf{B}_u$ and $\mathbf{B}_d$ are the state-space matrices. The supply chain state $\mathbf{x}$ at the next time step, $k + 1$, is determined using (5) as a function of the current supply chain state $\mathbf{x}$ plus the contribution due to the control action $\mathbf{u}$ and the demand. The control action $\mathbf{u}$ is the flow of commodities between nodes and is constrained by the available infrastructure resources.

C. Model Insight

In order to take advantage of some structural features, supply chain nodes should be ordered using the following policy: i) connections related to production lines are addressed first (flow nodes are numbered from upstream to downstream) after, ii) connections related to transport are addressed (flow nodes are numbered from upstream to downstream) then finally, iii) center nodes related to source, intermediate and destination nodes are numbered (the center nodes are numbered from upstream to downstream).

III. Operations Management

The use of Model Predictive Control (MPC) is justified by the ability to include constraints, predictions about the system behavior and exogenous inputs [6]. At each time step the controller first obtains the current state of the system. Then it formulates an optimization problem, using the desired goals, existing constraints, disturbances, and prediction information if available.

A. Problem Formulation

The cost function is generally a function of the supply chain states, control actions and desired states over the prediction horizon N_p,

$$J(\tilde{\mathbf{x}}_k, \tilde{\mathbf{u}}_k, \tilde{\mathbf{x}}_{ref}) = \sum_{l=0}^{N_p-1} f(\mathbf{x}(k+1+l), \ldots$$
$$\mathbf{u}(k+l), \mathbf{x}_{ref}(k+1+l)), \quad (8)$$

where $\tilde{\mathbf{x}}_k$ is the vector composed of the state-space vectors for each time step over the prediction horizon $\begin{bmatrix} \mathbf{x}^T(k+1) & ,\ldots, & \mathbf{x}^T(k+N_p) \end{bmatrix}^T$, $\tilde{\mathbf{u}}_k$ is the vector composed of the control action vectors for each time step over the prediction horizon $\begin{bmatrix} \mathbf{u}^T(k) & ,\ldots, & \mathbf{u}^T(k+N_p-1) \end{bmatrix}^T$, $\mathbf{x}_{ref}$ is the state-space reference vector and $\tilde{\mathbf{x}}_{ref}$ is the vector composed of the state-space reference vectors for each time step over the prediction horizon $\begin{bmatrix} \mathbf{x}_{ref}^T(k+1) & ,\ldots, & \mathbf{x}_{ref}^T(k+N_p) \end{bmatrix}^T$. The weights to be used in the objective function (8) are considered time-varying as a parameter that can change over time according to the variability of resources available. The MPC problem for the supply chain can now be formulated as:

$$\min_{\tilde{\mathbf{u}}_k} \quad J(\tilde{\mathbf{x}}_k, \tilde{\mathbf{u}}_k, \tilde{\mathbf{x}}_{ref}) \quad (9)$$
$$\text{s.t.} \quad \mathbf{x}(k+1+l) = \mathbf{A}\mathbf{x}(k+l) + \mathbf{B}_u\mathbf{u}(k+l) + \mathbf{B}_d\mathbf{d}(k+l), \quad (10)$$
$$\mathbf{y}(k+l) = \mathbf{x}(k+l), l = 0, \ldots, N_p - 1, \quad (11)$$
$$\mathbf{x}(k+1+l) \geq \mathbf{0}, \quad (12)$$
$$\mathbf{u}(k+l) \geq \mathbf{0}, \quad (13)$$
$$\mathbf{y}(k+l) \leq \mathbf{y}_{max}, \quad (14)$$
$$\mathbf{P}_{uu}\mathbf{u}(k+l) \leq \mathbf{u}_{max}, \quad (15)$$
$$\mathbf{x}(k+l) \geq \mathbf{P}_{xu}\mathbf{u}(k+l), \quad (16)$$
$$\mathbf{P}_{dx}\mathbf{x}(k+1+l) \leq \mathbf{d}_d(k+l), \quad (17)$$

where $\mathbf{d}_d$ is the vector introducing the market demand prediction, $\mathbf{y}_{max}$ is the maximum storage capacities per node, $\mathbf{u}_{max}$ the available infrastructure resources according to the supply chain layout, $\mathbf{P}_{xu}$ is the projection from the control action set $\mathcal{U}$ into the state-space set $\mathcal{X}$ and $\mathbf{P}_{uu}$ is the projection matrix from the control action set $\mathcal{U}$ into the infrastructure resource capacity set $\mathcal{U}_{max}$ and $\mathbf{P}_{dx}$ is the projection matrix from the state-space set into the disturbance set.

Constraints (12)–(17) are necessary in this framework as a guarantee that the supply chain behaves as expected:

- nonnegativity of states and control actions: negative storage and negative control actions (flows) are not physically possible, which is imposed by constraints (12)–(13);

- storage capacity: each supply chain node has to respect its storage capacity, this is captured in constraint (14);

- maximum control actions: the supply chain design in terms of available hardware used to implement desired flows is represented by constraint (15);

- feasible control actions: not all control actions that satisfy constraints (13) and (15) are feasible. The control action has to respect the existing amount per commodity in the each supply chain node at each time step. Constraint (16) imposes this relation;

- market demand: constraint (17) introduces the prediction if available.

B. Problem Insight

The MPC problem to solve has been formulated as a linear programming problem. In order to set the desired flow behavior for the supply chain through a pull-flow behavior, the following guidelines are given: i) the inventory reference at each center node is set as an upper-bound (by default the system will be producing to stock); ii) the weights at the flow nodes should be set as positive values in order to prevent the storage of commodities at these nodes, such that once a cargo starts a connection it should be delivered as soon as possible at the corresponding downstream node; and iii) weights at the center nodes need to be coordinated in order to promote the flow from upstream to downstream, that is to say, storing commodities at a downstream node has a higher benefit for 1 time period stay than the cost of transporting or producing the commodity.

IV. NUMERICAL EXPERIMENTS

In this section the MPC approach is applied for a supply chain composed of three tiers and handling raw materials and perishable goods.

A. Scenario Description

A time step of one day is considered for this supply chain. There are three tiers (supplier, distribution center and retail shop) in the supply chain (Fig. 2). Four commodities are supplied to the market: two raw materials (M_1 and M_2) and two perishable goods (G_1 and G_2) with a life time of 12 time steps (manufactured from the raw materials). The perishable goods are produced at the supplier tier according to a given proportion of raw materials (Table I). Once produced and made available at the supplier (node 5), the perishable good has only 12 time steps (days) to be delivered at the retail shop. Once delivered at the retail shop the due time of the perishable good is no longer tracked and it is assumed that the retail shop has into consideration a FIFO policy at the shelves.

		Raw materials		due time
		M_1	M_2	
perishable goods	G_1	1	1	12
	G_2	2	1	12

TABLE I. PERISHABLE GOODS MANUFACTURED IN THE SUPPLY CHAIN.

The supply chain is described by 7 nodes and 8 flows. These are used to capture the main features: i) Facilities –

supplier   distribution center   retail shop
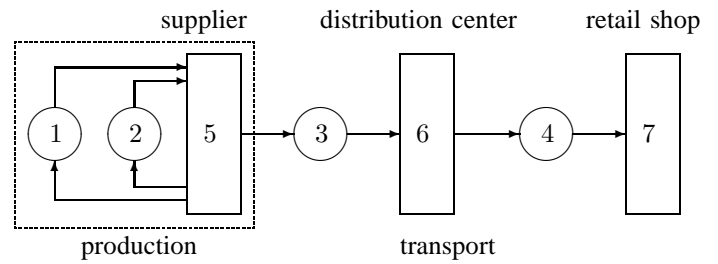
production   transport

Fig. 2. Supply chain composed of three tiers, handling two raw materials and two perishable goods (boxes: center nodes; circles: flow nodes).

described by three center nodes (supplier, distribution center and retail shop); ii) Production lines – used to produce G_1 and G_2. Both have a lead-time of 2 time steps, composed of two flows and one flow node. They both start and end at the supplier (node 5); and iii) Transport connections – are used to transport all commodities from the supplier towards the retail shop. Both have a due time of 2 time steps, therefore are composed of two flows and one flow node. The supply chain capacities are discriminated per commodity and maximum capacity at each node and flow (Table II and Table III). The lead time between the supplier and the retail shop is 4 time steps for all commodities. The lead time between starting producing to availability at the retail shop is 6 time steps due to the production time for both perishable goods.

		total	commodities			
			M_1	M_2	G_1	G_2
flow nodes	node 1	2	0	0	2	0
	node 2	3	0	0	0	3
	node 3	14	4	5	2	3
	node 4	14	4	5	2	3
connections	connection 1	inflow	2	0	0	2	0
		outflow	2	0	0	2	0
	connection 2	inflow	3	0	0	0	3
		outflow	3	0	0	0	3
	connection 3	inflow	14	4	5	2	3
		outflow	14	4	5	2	3
	connection 4	inflow	14	4	5	2	3
		outflow	14	4	5	2	3

TABLE II. CONNECTION CAPACITIES IN THE SUPPLY CHAIN.

		total	commodities			
			M_1	M_2	G_1	G_2
Capacity	node 5	4000	1000	1000	1000	1000
	node 6	2000	500	500	500	500
	node 7	400	100	100	100	100
Inventory	node 5	2760	900	900	480	480
	node 6	68	18	20	14	16
	node 7	68	18	20	14	16

TABLE III. NODE CAPACITIES IN THE SUPPLY CHAIN AND DESIRED INVENTORIES AT THE RETAIL SHOP.

According to the topology of the supply chain the incidence

matrix (relating nodes and flows) is given by,

$$\mathbf{D}(\mathcal{G}) = \begin{bmatrix} 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 \\ -1 & 1 & -1 & 1 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & -1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}. \tag{18}$$

B. Scenario Configuration

Consider that selling to public is starting in 20 days. Initially there are only inventory of raw materials at the supplier, in a sufficiently large amount to fulfill the expected demand. This means that all perishable goods must be produced. The market demand is assumed constant with value of 1 unit per time step for all commodities after day 20. The weights used for the construction of the optimization problem to be solved at each time step are indicated in Table IV, pulling commodities downstream but penalizing over-due time costs.

	commodity			
	M_1	M_2	G_1	G_2
Supplier	0	0	−1	−1
Distribution Center	−1	−1	−2	−2
Retail Shop	−2	−2	−20	−20
Over Due	–	–	200	250

TABLE IV.   COST FUNCTION WEIGHTS.

C. Numerical Results

For different prediction horizons N_{p} and demand knowledge, different numerical experiments are evaluated in terms of:

- over-due cargo: capability to manage perishable goods without loosing value;
- warehouse capacity used at the distribution center;
- deviation to desired inventory at the retail shop;
- the amount of goods moved for each due time at the supply chain, as a measure of the risk of loosing goods value.

With a bigger prediction horizon the methodology approach performance increases, either with or without demand knowledge (Table V). Only for $N_p = 6$ perishable goods with a due time lower than de maximum lead-time (6 time steps) are being moved (Table VI). For N_p equal or higher to 8 no over-due happens for both scenarios. The performance in terms of warehouse capacity used at the distribution center and the deviation of inventory levels at the retail shop are equal for N_p equal or higher to 8. For this case scenario a prediction horizon higher then maximum due time available at the supply chain is not necessary. Recall that the maximum lead-time in the supply chain is lower than the maximum due time at the supply chain ($6 < 12$). In the case of knowledge of the demand, the inventory levels at the retail shop increase until the desired value is reached. Even when the demand starts,
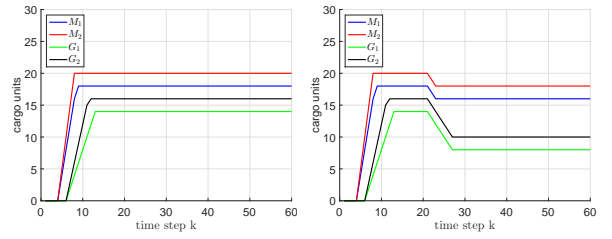

Fig. 3.   Inventory levels at the retail shop for known demand (left) and unknown demand (right).
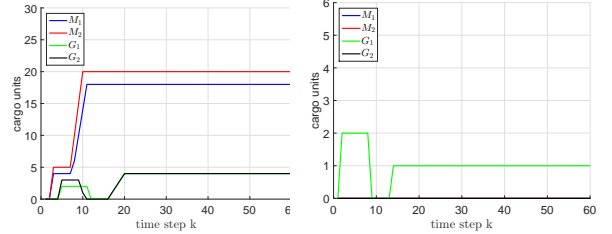

Fig. 4.   Inventory per commodity at the distribution center (left) and Work In Progress (WIP) for connection 1 (right).
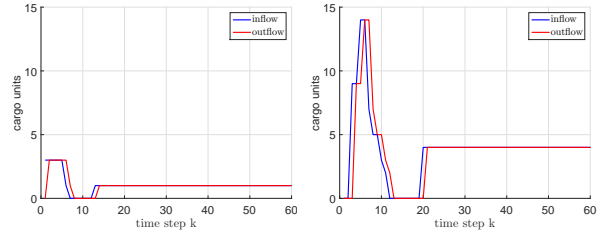

Fig. 5.   Inflow and outflow for connections 2 (left) and 4 (right).

at day 20, the inventory level remains unaltered. For the case with no knowledge of the demand market, once the demand starts, inventory levels drops and remains for the rest of the simulation (see Fig 3).

1) Insights in Prediction Horizon $N_{\mathrm{p}} = 14$: Due to a sufficiently large prediction horizon operations management is capable to fulfill the market demand for all commodities, while eliminating waste (no unnecessary production or unjustified transport). For detail on operations see Fig 4–5.

2) Insights in Prediction Horizon $N_{\mathrm{p}} = 6$: Due to a question of short vision a low performance is achieved for the supply chain (Fig. 6). The proposed approach is still able to pull the commodities (raw material and perishable goods) taking into account the market demand but at the cost of over-due cargo. It is possible to see that for the final time steps the inventory of G_1 and G_2 are dropping at the retail shop (in Fig. 7). Due to unnecessary production, too many resources of M_1 have been consumed, leading to the run out of stock at the supplier. Production of G_1 and G_2 is halted as well as transport.

V.   CONCLUSION

In this paper an MPC heuristic was proposed to address operations management for perishable goods in supply chains. The approach is capable to track the remaining time until due time making it suitable to handle perishable goods. With this

Horizon	Over Due Goods		Inventory used at Distribution Center		Inventory error at Retail Shop	
	Known Demand	Unknown Demand	Known Demand	Unknown Demand	Known Demand	Unknown Demand
$N_\mathrm{p} = 6$	111	116	3710	3655	492	803
$N_\mathrm{p} = 8$	0	0	2436	2084	471	1009
$N_\mathrm{p} = 12$	0	0	2436	2082	471	1079
$N_\mathrm{p} = 14$	0	0	2436	2082	471	1079

TABLE V.   PERFORMANCE EVALUATION FOR DIFFERENT PREDICTION HORIZONS.

| Horizon		Commodities Due Times											
		dt_1	dt_2	dt_3	dt_4	dt_5	dt_6	dt_7	dt_8	dt_9	dt_{10}	dt_{11}	dt_{12}
Kown Demand	$N_\mathrm{p} = 6$	72	72	0	0	0	0	0	0	30	30	213	213
	$N_\mathrm{p} = 8$	0	0	0	0	0	80	82	0	30	30	120	122
	$N_\mathrm{p} = 12$	0	0	0	0	0	80	82	0	30	30	120	122
	$N_\mathrm{p} = 14$	0	0	0	0	0	80	82	0	30	30	120	122
Unkown Demand	$N_\mathrm{p} = 6$	69	69	0	0	0	0	0	0	30	30	215	215
	$N_\mathrm{p} = 8$	0	0	0	0	0	0	0	0	100	102	104	106
	$N_\mathrm{p} = 12$	0	0	0	0	0	0	0	0	98	100	102	104
	$N_\mathrm{p} = 14$	0	0	0	0	0	0	0	0	98	100	102	104

TABLE VI.   EVALUATION OF DUE TIME FLOWS.
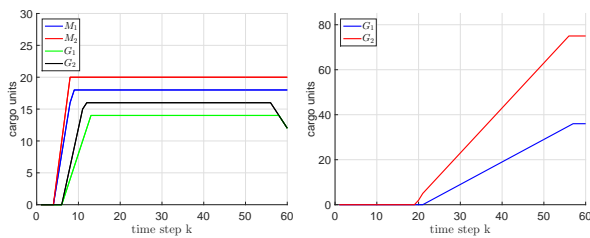
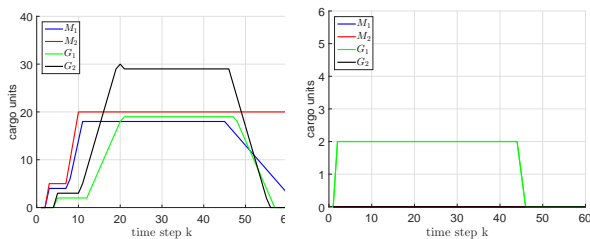Fig. 6.   Inventories at the retail for known demand (left) and unknown demand (right).

Fig. 7.   Inventory per commodity at the distribution center (left) and Work In Progress (WIP) for G_1 (right).

capability it is possible to launch production orders according to the market demand, reducing the risk of losing value due to over production. Operations are synchronized throught the supply chain and intermediary nodes can be used soleley for X-docking activity. The approach is modular being easily scalable for large-scale systems. As future research the inclusion of a forecast module for market demand is worth to be considered and the analysis of the Forrester effect on perishable goods.

ACKNOWLEDGMENT

REFERENCES

[1] Ballou, R.H.: Business Logistics – Supply Chain Management: Planning, Organizing, and Controlling the Supply Chain. Prentice Hall (2004)

[2] Kuo, J-C., Chen, M-C.: Developing an advances Multi-Temperature Joint Distribution System for the food cold chain. Food Control **4** 559–566 (2010)

[3] Lin, X., Negenborn, R.R., Lodewijks, G..: Towards quality-aware control of perishable goods in synchromodal transport networks. In: Proceedings of the 5th IFAC Conference on Sensing, Control and Automation for Agriculture (IFAC AgriControl 2016), pp. 132–137, Seattle, Washington, August (2016)

[4] Wang, W., Rivera, D.E.: Model Predictive Control for Tactical Decision-Making in Semiconductor Manufacturing Supply Chain Management. IEEE Transactions on Control, Systems Technology, **16**, 5, 841–855 (2008)

[5] Alessandrini, A., Gaggero, M., Tonelli, F.: Min-Max and Predictive Control for the Managemetn of Distribution in Supply Chains. IEEE Transactions on Control, Systems Technology, **19**, 5, 1075–1089 (2011)

[6] Maciejowski, J.M.: Predictive control with constraints. Harlow, UK: Prentice Hall (2002)

[7] Maestre, J.M., Muñoz de la Pena, D., Camacho, E.F.: Distributed MPC: a supply chain case. In: Proceedings of the 48th IEEE CDC and 28th CCC, pp. 7099–7104, Shanghai, China, December (2009)

[8] Geyer, T., Larsson, M., Morari, M.: Hybrid emergency voltage control in power systems. In: Proceedings of the European Control Conference. Cambridge, UK. paper 322 (2003)

[9] Negenborn, R.R., Van Overloop, P.J., Keviczky, T., De Schutter, B.: Distributed model predictive control of irrigation canals. Networks and Heterogeneous Media **4** 359–380 (2009)

[10] Nabais, J.L., Negenborn, R.R., Carmona-Benítez, R., Mendonça, L., Botto, M.A.: Hierarchical Model Predictive Control for Multiple Commodity Transportation Networks, Distributed MPC Made Easy, Springer (2013)

[11] Ahuja, R.K., Magnanti, T.L., Orlin, J.B.: Network Flows. New Jersey, Prentice Hall (1993)

[12] Nabais, J.L., Negenborn, R.R., Carmona-Benítez, Mendonça, L.F., Lourenço, J., Botto, M.A.: Multi-Agent Architecture for Supply Chains using a Predictive Pull-Flow Perspective. Proceedings of the 11th Int. Conf. on Practical Application of Agents and Multi-Agent Systems, pp.94–105, Salamanca, Spain, May (2013)

[13] Kvasnica, M., Grieder, P., Baotić, M.: Multi-parametric toolbox (MPT), (2004)