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Plant Layout and Pick-and-place Strategies for Improving Performances in Secondary Packaging Plants of Food Products†

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The aim of secondary packaging plants is to pick food products from a conveyor belt and to place them into boxes. The typical configuration of these packaging plants consists of a set of sequential robot stations, performing pick-and-place cycles from one conveyor to another parallel one, which transport the products and the boxes to be filled. Depending on the relative movement of the two conveyors, the plant operates in co-current or counter-current flow configuration. Undesired perturbations in the product flow rate from its nominal value can lead to critical events, i.e. unpicked product at the end of the first conveyor or not completely filled boxes. Even if the structures of co-current flow and of counter-current flow plants are very similar, their behaviour in non-nominal or perturbed conditions can be significantly different.

The aim of this paper is to deeply investigate the behaviour of these two kinds of secondary packaging lines, evaluating their performances in the case of different pick-and-place strategies, using discrete events simulation techniques.

Results show to which extent the different proposed control strategies can improve the performances of both co-current and counter-currents plants and, in particular, how co-current plant layouts can achieve performances that are equivalent to, or perhaps even better than, those that can be obtained with a counter-current plant layout, which cannot be freely used because it has been patented. The simulation tool, control algorithms and results presented can help packaging plant designers for choosing the most appropriate solutions and for properly sizing the plant. Copyright © 2012 John Wiley & Sons, Ltd. Q1

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INTRODUCTION

Secondary packaging is the last step in most production plants. During this phase, food products, such as pastries, chocolate and candies, as well as meat products, which could have already been singularly packed into a protection envelope or paper, are placed into boxes ready for the market.[1–3] The layout of boxes can be quite different from product to product, and in some cases, it is rather elaborate. The number of units to be placed in each box and their layout are fixed and known for each given product.

Typical secondary packaging plants consist of two aligned belts conveying the product ready for packaging and the empty boxes to a series of robot stations in which the product delivered on one belt is picked and placed in the boxes carried by the other belt.[4–6] In general, the pick-and-place cycle rate of one single robot is lower than the rate of incoming products on the conveyor belt, so that it cannot pick all the units of product and fill up all the boxes. For this reason, more robotic cells are typically arranged in series across the conveyor belts.[4] In this way, product units pass sequentially throughout

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the working areas of the robotic cells, each one of which picks a fraction of the incoming products and places them into available empty positions in the boxes. Indeed, in a properly working plant, the joint action of the robotic cells should ensure that all the incoming products are picked from the conveyor belt and all the boxes are properly filled up when leaving the plant. This goal is not trivial. On one side, it is needed that the inflow of products on the conveyor belt and of empty places in the boxes is balanced so that each single unit of product can be placed into a suitable position in a box. On the other side, it is required that the work of the robots is properly organized so that no matching between an incoming unit of product and an empty position in a box is missed. The plant is malfunctioning whenever some product is not picked from the conveyor belt by any robot so that it becomes wasted or a not properly filled box leaves the last robotic cell. Both such dropout conditions represent a loss and should therefore be avoided. It should be noted that the cost of a not properly filled box, mainly given by the labour required to manually handle and complete the filling, is in general quite larger than the cost of an unpicked product. The level of success of a packaging plant is then typically evaluated looking at the amount of dropouts that occur in given operational conditions.

The pick-and-place process is distributed over the different robotic cells, and also within each robotic cell, it targets the whole working area. As depicted in Figure 1, any unit of product, which **F1** is on the conveyor belt within the working volume of a given robot, can be picked and delivered to an empty place in a box, which also needs to be in the working area of the robot. To avoid dropouts, it is needed that 'average flows' of product units and of empty places in the boxes are equal in the area in which the pick-and-place activity is carried on. It should be noted that such flows are not the instant flows entering the robotic cells.

Indeed, the inflow of product on the conveyor belt in real plants is often not constant. Low frequency perturbations, which can be commonly observed in food production plants, can be the consequence of variations in the production rate of upstreaming machines. Similarly, high frequency variations of the inflow of the product are also a common feature and depend on several other factors. The randomness that often affects the position of the product on the conveyor belt is one of them as in the case of dropping of products from trays or moulds in chocolate moulding lines onto the product conveyor belt. Such changes in flow can indeed cause dropouts.

For what concerns the possibility that incomplete matching of product units with empty positions in the boxes occurs in the pick-and-place process, it should be noted that the whole process is quite complex and is affected by different factors such as the logic by which the different products to be

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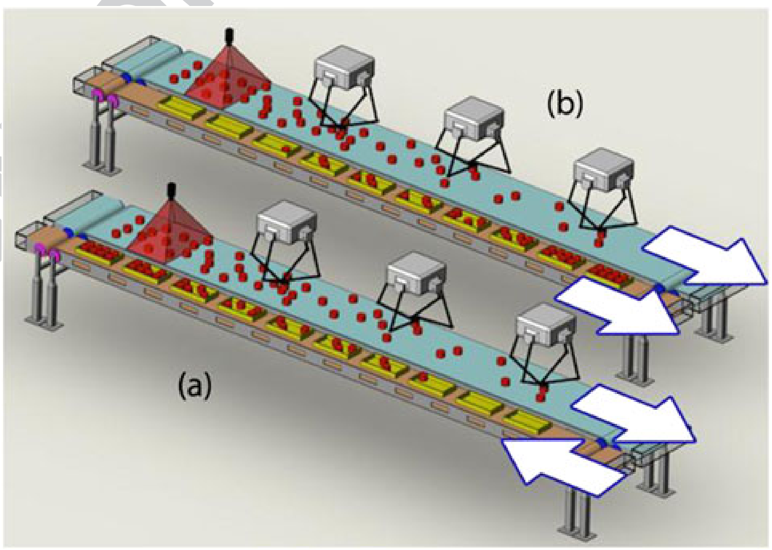

Figure 1. The packaging plant in the counter-current flow (a) and co-current flow (b) configurations with three robot isles.

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picked are assigned to the different robots and the logic underlying the pick-and-place cycle.[7] It is also important to underline that the different robotic cells are not isolated but operate sequentially on the same conveyor belts, and therefore, they influence each other with complex dynamics in which delays and nonlinearities play an important role. In this regard, the relative movement of the product conveyor belt and the box conveyor belt represents an important variable, for what concerns the total performances of the plant. Two solutions are in fact possible. In the first one, the two belts move in the same direction, whereas in the second solution, they move in opposite directions. The first case is usually referred to as co-current flow setting, and the second one as counter-current flow setting.[8] This last setting, which is known by plant designer to be more stable against flow rate perturbations, has been patented[9] and therefore cannot be adopted without licence or permission. These two layouts are represented in Figure 1 for the case of conveyor belts serving a series of three robotic cells.

To understand why counter-current plants are nowadays preferred, consider the following simple example. In co-current flow setting, define as robot number 1 the first to which the conveyor belt delivers the products to be packed, i.e. the first that receives the boxes to be filled. It has therefore plenty of product units to pick-and-place in many empty places in the boxes. On the contrary, robot number 3, which is the last to which the conveyor belt delivers the products to be packed, has few product units left on the conveyor belt and has also few free places left in the boxes. It could therefore happen that robot number 3 is unable to complete a box that is leaving its working space because no unit of product is available in its working space on the conveyor belt. If in such condition the conveyor of the boxes is slowed down to wait for a product to be placed in the incomplete box, the consequence is that also the boxes in the workspace of robot 1 are slowed so that robot 1, which has plenty of units to pick, fills up all the boxes in its working space. As a consequence, when later on these boxes arrive in the workspace of the following robots, these last cannot make any picking because they do not have empty boxes where to place incoming units of product. Consequently, there are dropouts of the product from the conveyor belt. If in such condition the belt of the boxes is accelerated to try to have more empty places in the boxes for robots 2 and 3, robot 1 reduces the number of placements in the boxes, and this could lead again to the condition in which an incomplete box is leaving the working space of the last robot. This kind of unstable behaviour that could occur is also related to the fact that the speed of the two conveyor belts is not the same because the density of units of product on the conveyor belt and the density of places in the boxes are not the same per unit length. In general, the two belts have to move at different speed, and there are belt segments, between the robot cells, where no pick-and-place can occur. Consequently, the boxes to be filled are aligned with different portions of the product conveyor belt during their movement throughout the working spaces of the different robots.

In the counter-flow configuration, robot 1, which has plenty of products to pick from the conveyor, receives almost full boxes and should therefore be easily able to pick products to complete their filling. On the contrary, robot number 3 receives few units on the conveyor together with empty boxes so that it should be easily able to pick all the units and put them in the boxes. In such condition, a slowdown of the speed of the box belt to avoid that an incomplete box leaves the working space of robot 1 is less likely to cause instability because its consequence is that more units to be picked will reach robots 2 and 3, which, however, have less filled boxes that they will just fill more.

The whole process dynamics is quite complex with complex interaction mechanisms between the pick and place activities of the different robotic cells. Different solutions can be adopted to improve the flexibility of the system and to relax undesired interactions between robotic cells that appear to affect the performances of the packaging line in perturbed conditions. The plant can be modified introducing in each robotic cell a buffer in which units of product, delivered by the conveyor belt, can be stored when there are no empty places available in the boxes. Similarly, the product units in the buffer can be transferred to the boxes when there is no product available on the conveyor belt. Although this qualitative analysis seems reasonable, plant designers require quantitative methods to a priori evaluate plant performances. No mathematical models, in terms of dynamic equations, is nowadays available neither can they be reasonably derived to satisfactorily describe the behaviour of the whole system analytically. It is however possible to build a rather accurate simulator to study the behaviour of this system.

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The aim of this paper is to evaluate, by means of an extensive simulation study, the performances of co-current and counter-current flow packaging plants under different operative settings, in nominal and perturbed conditions, considering also the possible presence of buffers. The simulation tool that has been developed by our research group is presented first, together with some implementation details. The results of a rather extensive simulation study that has been carried out with its help are then illustrated. It is interesting to anticipate that the study allowed to find out unexpected characteristics of packaging plants and in particular to show that, adopting specific control strategies, co-current flow plants can achieve performance levels comparable with those of counter-current flow ones that, contrary to expectations, present some drawbacks and weaknesses.

The paper is structured as follows: Simulation suite of secondary packaging plants section introduces the simulator that has been developed and used, whereas Simulation study section presents the different simulation conditions adopted in the paper. The results of the performance evaluation and comparison of the different scenarios are reported and discussed in 'Discussion of simulation results' section, whereas conclusions are drawn in 'Conclusions and future research directions' section.

SIMULATION SUITE OF SECONDARY PACKAGING PLANTS

A flexible computer simulator, completely implemented in MATLAB® (MathWorks, Natick, MA, USA), has been developed to study secondary packaging plants with the structure outlined in the previous section. In the simulator, the system is represented in discrete time form with a discrete time interval Δt that can be arbitrarily chosen. Its geometric layout, as well as the number of robotic cells, with or without product buffers, can be varied properly choosing a set of input parameters. Similarly, other operative conditions such as product inflow, boxes layout, belt speed, co-current or counter-current flow and so on can be conveniently chosen through dedicated parameters. Actually, the simulator consists of a suite of three modules that perform different functions. Q2

The first module mainly consists in a graphic interface that allows setting all the relevant parameters, which are needed to fully characterize the geometric layout of the plant, to specify algorithms and logics for its operation and to generate the distribution of the product units and of the boxes on the two conveyor belts. Such parameters are rather consistent in number and can be grouped in the following categories:

- Simulation times, which include the total duration of the simulation, the discrete time interval used for the simulation and the time interval that is used to generate the distribution of product units on the conveyor belt. This last time interval can differ from the one used in the simulation because in general, it must be very short to properly compute product distributions when high frequency variations in the flow are considered.
- Geometric parameters of conveyor belt, such as the width of the conveyor belt, its speed, its distance from the box conveyor belt and the radius of the single product units that, for simplicity, are supposed to be circular. Indeed, also the co-current flow or the counter-current flow is chosen within this parameter group.
- Geometric parameters of the buffer that allow to specify the possible availability of a buffer in the robotic cells and to describe its characteristics in terms of dimension and number of buffer positions.
- Geometric parameters of boxes that fully characterize them and include also the distance between boxes on the belt.
- Parameters of robotic cells, which are used to characterize each robotic cell as well as to indicate their total number. The simulator supports Delta robots. For this reason, the working space is assumed circular. Indeed, other kinds of robotic cells, with different working space and parameters, could be added. Robot parameters include also the specifications needed to compute the duration of each single pick-and-place cycle, i.e. the maximum allowed acceleration and speed.
- Parameters of the scanner define the position in which the scanner that, in the real plant, performs the optical recognition of the units of product and identifies their position on the conveyor belt by means of artificial vision techniques is located. Because in the real plant each recognized unit of

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product is assigned to one or more robotic cells that must take care of picking it and placing it in the boxes, the parameters of the scanner include also the indication of the assignment algorithm. Such assignment can indeed be performed according to several logics. In the simulation suite, five different assignment and pick-and-place logics have been implemented so far, but the modularity of the programs would easily accommodate new assignment algorithms. In any logic, when in the working space there are more units that can be picked, then the one that is going to leave sooner the working space is picked first. Similarly, when more empty positions are available in the working space, the one that is going to leave sooner the working space is filled first. When the buffer is available, units are delivered to the buffer only when there are no empty places in the boxes, and units are picked from the buffer only when there are no units on the conveyor belt. The assignment and pick-and-place logics implemented so far in the simulation suite are as follows:

- No assignment at all. Each robot can pick any unit of product in its working space and place it in any empty position in the boxes.
- Incoming units of product are cyclically assigned to the robotic cells so that they are equally partitioned among the robots, obtaining a balanced workload of the cells. The last cell, however, picks also the units, which have been missed by the previous ones.
- The same rules of Logic 2 for the picking phase, applying also a cyclical assignment of the empty places in the boxes to the different cells. Applying this rule, a robot cannot place units of product in any position but only in the ones that have been assigned to it. Obviously, the last robot is free to fill up any empty position.
- This logic is used only when the buffer is available. Besides implementing Logic 3, the manipulator picks a unit of product whenever there is an empty position available to place it. If there are no available positions in the boxes, the unit of product is picked and placed in the buffer only when it is in the second half of the working space. Similarly, units of product are picked from the buffer only when an empty place in the boxes is present in the second half of the working space.

Obviously, in the simulator, there is no need to perform the recognition of product units and of their position because it is well known. However, the information about the scanner position is used to simulate the assignments, which are performed only when the product units pass under the scanner.

- *Seed for random generations*: set the seed that is used for initializing the generation of random data (which is needed to replicate the simulation, if required).
- *Instant flow profile of product on the conveyor belt*. Such flow is expressed in units per second and is given as a function of time on the whole time horizon on which the simulation has to be computed. Through the graphic interface (see Figure 2), the flow profile is specified as the sum **F2** of at most 20 different elementary functions that have to be chosen from the following list:

- Constant function, for which the value, the initial time and the duration (within the total simulation time) have to be specified.
- Sinusoid function, for which the average value is zero and the peak value and the period have to be specified. It is used to model deterministic periodical fluctuation of the flow rate of the incoming products.
- Random noise function, with zero mean and uniform distribution, for which the amplitude has to be specified. It can be used, for example, to model position uncertainties affecting product units during their load of the conveyor belt.
- Random noise function, with zero mean and Gaussian distribution, for which the standard deviation has to be specified.
- Trapezoidal function for which the maximum value has to be specified together with the starting time, the duration of the linear increasing interval, the duration of the constant interval and the duration of the linearly decreasing interval. All of them have to be within the total simulation time. This profile can be used to model upstream temporary supply changes to the packaging lines like in chocolate moulder machines during their start and stop phases.

Once the product flow profile has been provided, the generation of the units of product on the conveyor belt is computed for the whole duration foreseen for the simulation. The units on the

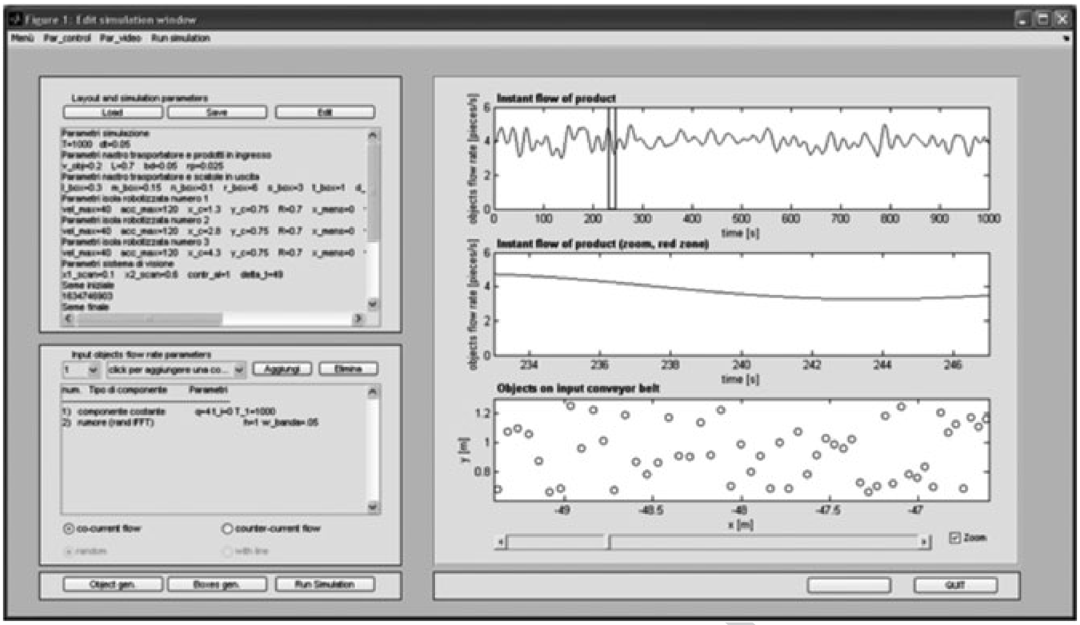

Figure 2. Graphic interface of the first module of the software. All the relevant parameters can be set on the left side of the window, whereas the right side of the window is devoted to displaying the inflow of product and the displacement of the items on the conveyor belt.

conveyor belt are graphically displayed together with the graph of the instant unit flow and the main parameters used for the simulation as shown in Figure 2.

- *Output data presentation*. These parameters specify the output data that are of interest and that have to be collected. This is particularly important in connection with the possibility, which is offered by the simulation suite, to provide a video showing the functioning of the packaging line. With these parameters, it is possible to specify if the video has to be produced for the whole simulation or if it has to be provided only for those time intervals in which some specific events occur (e.g. product dropout and/or unfilled box). A more extended description of the output options is provided later on when presenting the third module of the suite that enables the output visualization.

Once simulation parameters have been defined using this first module and its graphic interface, they are saved, together with the computed distribution of product units on the conveyor belt, in a file and are ready to be used by the next module. The file can also be reloaded in the first module that can then be used to edit the data avoiding the need to input again all of them. This feature can be used to easily create sets of data files that differ only for a few parameters whose influence on the simulation can be tested, ensuring that all remaining parameters are unchanged.

The second module of the simulation suite just simulates the behaviour of the whole packaging plant and prepares the required output data that are stored in a file that is then used by the following module.

The last module of the suite allows to visualize the relevant data of the simulation. Besides the movies of the working plant in the selected time intervals, output information is provided with tables, which mainly summarize the number of dropouts and the time instant at which they occur, and with plots, which provide visual information on different features of the packaging plant.

The plots that can be visualized over the whole simulation horizon are as follows:

- flow of product units on the conveyor belt;
- number of drop outs (units of product);
- number of drop outs (boxes);
- work load of the different robots in pick-and-place cycles per minute;
- number of objects in the buffer.

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The visualization module is provided with a feature that allows visualizing, together with each whole plot, also its details within a suitable window that can be moved over the whole simulation horizon and is expanded in a second plot. It is therefore possible to examine the details of each plot in the relevant zones.

SIMULATION STUDY

With the previously described simulation suite, a study has been undertaken to evidence the characteristics of secondary packaging lines in connection with different possible plant layouts and operational conditions. In particular, the study has been aimed to evaluate the possible advantages that can be obtained using the counter-current flow layout with respect to the co-current flow and to determine the advantages that the use of buffers in the robotic cells can provide to the overall performances.

Obviously, such analysis is meaningful only when the conveyor belt feeds more than one robotic cell. The case with two cells only seems to be still rather particular. It has therefore been decided to develop the analysis for a plant with three robotic cells. This is the smallest plant configuration in which there is at least one robot that is neither the first nor the last one. A larger number of robotic cells would increase the complexity of the system and consequently the amount of required computation and data storage. Typical parameters of commercial robots and packaging lines have been chosen to represent the system. All such parameters are shown in Table 1. **T1**

From the heuristic analysis of the problem outlined in the introduction, it appears that the conditions that can provide troubles to the system are likely to occur when the flow of product units on the conveyor is changing in time and when the flow of product is close to $Q_{\max}$, which is the maximum pick-and-place rate of the plant. To conduct the analysis in meaningful conditions, a first study has been conducted to find out such maximum value $Q_{\max}$. To this extent, different simulations were computed. In each simulation, the product inflow was kept constant for 1 h. The value of the flow was increased from simulation to simulation until dropouts started to occur. The maximum value $Q_{\max}$ has been chosen to be the highest inflow value for which there have not been dropouts in three distinct simulations. Note that with the obtained flow values, there are about 18.000 pick-and-place events per Q3 hour. Therefore, $Q_{\max}$ has been derived as the highest constant flow for which about 54.000 events have been safely processed. The numerical value that has been experimentally derived is 5.01 units per second in the counter-current flow setting. Unexpectedly, in the co-current setting, the maximum flow is 5.52 units per second, higher value than in the counter-current configuration. The reason for this difference is explained in the following section. The value of $Q_{\max}$ has been derived when the units of product to be picked and placed are assigned to the different robotic cells according to the Logic 2 (incoming units of product are cyclically assigned to the robotic cells so that they are equally partitioned among the robots. The last cell, however, picks also the units that have been missed by the previous ones).

To test the performances of the plant in different conditions, it was decided to use an inflow that is the sum of two components: a constant one, whose value is expressed as a percentage of $Q_{\max}$ and sets the 'working point' of the plant, and a (zero mean) sinusoidal one, whose peak amplitude is again expressed as a percentage of $Q_{\max}$ whereas its frequency can assume different values. Such continuously varying component, modelled by sinusoids of different periods, stresses the plant rather consistently. The simulation horizon was assumed to last 1 h. The speed of the box conveyor belt has been set constant so that the inflow of empty incoming spaces is also constant and equal to the total number of generated units of product divided by the total simulation time. Even if 'intelligent' rules could be used to modulate the speed of the conveyor according to the inflow of the product, we assumed it constant to

Table 1. Commercial picker robot parameters.

Working diameter	1130 mm
Working height	250 mm
Maximum speed	10 m/s
Maximum acceleration	100 m/s^2
Maximum torque of spindle	1 Nm

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better highlight the degree by which the different picking strategies and possible plant layouts can cope with changes and irregularities in product inflow.

Simulation data were generated for the 60 different input sequences resulting from all the combinations of the following parameters values:

- constant value, equal to 70%, 80% and 90% of Q_{max};
- amplitude of the sinusoidal signal equal to 10%, 15%, 20% and 25% of Q_{max};
- period of the sinusoidal signal equal to 1, 2, 4, 8 or 16 min.

A second simulation study has then been conducted adopting an incoming product flow rate described as the sum of a constant function and a random component modelled by a uniformly distributed white noise, filtered by a low-pass filter at different frequencies. The parameters for such random noise are

- amplitude of the uniform white noise equal to 10%, 15%, 20% and 25% of Q_{max};
- cut-off frequency of the low-pass filter equal to 1, 0.1, 0.05, 0.01 and 0.005 Hz.

Also, for this second simulation study, there are 60 different input sequences resulting from all possible combinations of the relevant parameters.

Complete output data (S1) and video clips (S2–S7) are available in the supplementary material section of the journal online. In the following section, instead, simulation results and output data are presented in a more condensed way for reference and discussion.

DISCUSSION OF SIMULATION RESULTS

The first unexpected result, as previously evidenced, has been the fact that the maximum steady-state product flow that can be handled by the plant is slightly higher in the co-current flow setting. The explanation for this occurrence lies in the fact that when there is a high flow rate, the robots comes to a point in which they are chasing the units that are almost leaving their working space and similarly are putting them in empty box positions that are also leaving the robot working space. When this happens, distances that have to be covered during a pick-and-place cycle are shorter for the case of co-current flow layout, as it can be seen from Figure 3. The consequence F3

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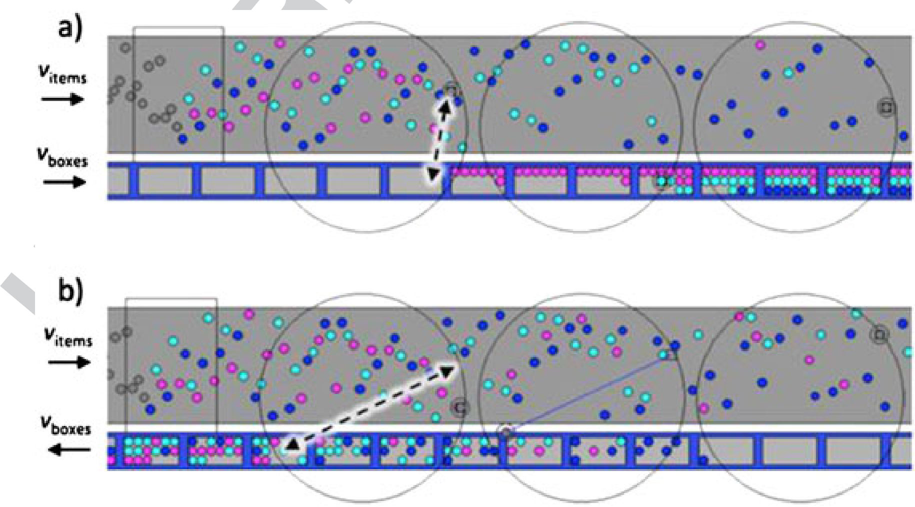

Figure 3. Example of the behaviour of a packaging plant in co-current (a) and counter-current (b) flow configuration under stress condition. Circles represent the working areas of the three manipulators. Dashed arrows represent two examples of trajectories in the case of heavy working condition, in both co-current and counter-current flow configurations. As can be seen, the path length of pick-and-place cycles in the case of co-current plant is shorter.

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is that a higher pick-and-place rate is possible in the co-current setting. Actually, in the counter-current environment, there is a kind of catastrophic behaviour: when the unit inflow increases, the robots increase the pick-and-place rate until they start to work in a less favourable condition with longer pick-and-place trajectories that consequently decrease the rate. When this happen in the first robotic cell, the following ones receive more units that make them soon collapse, according to an avalanche effect, that drastically reduces the overall pick-and-place capacity of the plant.

The main characteristics that this study has evidenced for the different pick-and-place strategies as well as for the influence of co-current and counter-current settings with and without buffer are now synthetically analysed.

A comparative overview of the different strategies is reported in Tables 2–5, where the performances **T2 – T5** of the different strategies are evaluated in terms of number of dropouts. Tables 2 and 3 summarize the results obtained stressing the plant with an inflow of product constituted of a constant and a sinusoidal component. Such results are expressed in terms of not completely filled boxes and runoffs, respectively. The results of the simulations performed with an inflow composed by a constant added to a random component are shown in Tables 4 (not completely filled boxes) and 5 (runoffs). Each column of the tables contains five numbers that synthetically describe the results of a group of 60 simulation conducted with a particular control strategy and with or without buffers. More in detail, results are expressed as follows:

- mean value of the percentage of dropouts (runoff or not completely filled boxes), with respect to the total number of objects or boxes handled during each simulation;
- maximum value found in the worst simulation of the group;
- percentage of simulations that have results between 0% and 2% of dropouts, with respect to the 60 simulations;
- percentage of simulations that have results between 2% and 5% of dropouts;
- percentage of simulations that have results worst than 5% of dropouts.

In general, the best results have been obtained implementing Strategies C and D with buffers. Strategy D results however to be better because it also improves the workload of the robots, reducing unnecessary movements. In particular, Strategy D also allows co-current flow configured plants to minimize the gap of performance that this kind of configuration shows with respect to the counter-current setting, obtaining almost the same number of dropouts.

Table 2. Results, in terms of percentage of not completely filled boxes (NCFB), obtained in the simulations performed with product inflow profiles that are the sum of a constant and a sinusoid of different period and amplitude.

	Strategy	A		B		C		D
Co-current flow	Buffer	No	Yes	No	Yes	No	Yes	Yes
Co-current flow	Strategy	A		B		C		D
	Buffer	No	Yes	No	Yes	No	Yes	Yes
	Mean value	27.27	11.37	17.74	9.70	8.79	3.62	3.98
	Maximum value	40.43	30.28	33.17	28.44	27.99	19.82	22.61
	$0\% \leq$ NCFB $\% < 2\%$	5.0%	45.0%	26.7%	48.3%	53.3%	66.7%	66.7%
	$2\% \leq$ NCFB $\% < 5\%$	0.0%	0.0%	0.0%	1.7%	1.7%	6.7%	5.0%
	NCFB $\% \geq 5\%$	95.0%	55.0%	73.3%	50.0%	45.0%	26.7%	28.3%
Counter-current flow	Mean value	35.27	31.69	16.52	10.13	11.65	5.16	3.92
	Maximum value	85.06	80.48	45.32	44.92	29.78	21.22	21.22
	$0\% \leq$ NCFB $\% < 2\%$	45.0%	46.7%	55.0%	65.0%	61.7%	70.0%	68.3%
	$2\% \leq$ NCFB $\% < 5\%$	0.0%	0.0%	0.0%	0.0%	1.7%	0.0%	3.3%
	NCFB $\% \geq 5\%$	55.0%	53.3%	45.0%	35.0%	36.7%	30.0%	28.3%

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Table 3. Results, in terms of runoffs, obtained in the simulations performed with product inflow profiles that are the sum of a constant and a sinusoid of different period and amplitude.

	Strategy	A		B		C		D
Co-current flow	Buffer	No	Yes	No	Yes	No	Yes	Yes
Co-current flow	Strategy	A		B		C		D
	Buffer	No	Yes	No	Yes	No	Yes	Yes
	Mean value	3.86	1.81	2.73	1.70	1.31	0.43	0.52
	Maximum value	7.42	6.63	7.11	6.58	6.29	4.38	4.86
	0% ≤ runoff % < 2%	15.0%	60.0%	40.0%	61.7%	73.3%	90.0%	88.3%
	2% ≤ runoff % < 5%	55.0%	28.3%	38.3%	28.3%	21.7%	10.0%	11.7%
	Runoff % ≥ 5%	30.0%	11.7%	20.0%	8.3%	5.0%	0.0%	0.0%
Counter-current flow	Mean value	5.52	4.50	2.22	1.41	1.27	0.37	0.37
	Maximum value	15.73	13.93	8.40	8.16	6.29	4.25	4.26
	0% ≤ runoff % < 2%	36.7%	36.7%	53.3%	70.0%	73.3%	91.7%	90.0%
	2% ≤ runoff % < 5%	18.3%	21.7%	30.0%	21.7%	21.7%	8.3%	10.0%
	Runoff % ≥ 5%	45.0%	41.7%	16.7%	8.3%	5.0%	0.0%	0.0%

Table 4. Results, in terms of percentage of not completely filled boxes (NCFB), obtained in the simulations performed with product inflow profiles that are the sum of a constant and a random noise, with different amplitude and filtered with low-pass filter with different cut-off frequency.

	Strategy	A		B		C		D
Co-current flow	Buffer	No	Yes	No	Yes	No	Yes	Yes
Co-current flow	Strategy	A		B		C		D
	Buffer	No	Yes	No	Yes	No	Yes	Yes
	Mean value	10.49	3.16	5.72	2.31	2.06	0.42	0.45
	Maximum value	27.9	16.6	21.62	12.23	13.25	6.37	6.56
	0% ≤ NCFB % < 2%	26.7%	65.0%	48.3%	66.7%	70.0%	91.7%	91.7%
	2% ≤ NCFB % < 5%	8.3%	6.7%	11.7%	15.0%	13.3%	5.0%	5.0%
	NCFB % ≥ 5%	65.0%	28.3%	38.3%	18.3%	16.7%	3.3%	3.3%
Counter-current flow	Mean value	28.89	22.04	6.00	2.56	4.84	1.35	1.08
	Maximum value	81.66	77.38	20.68	12.52	16.37	9.3	9.24
	0% ≤ NCFB % < 2%	53.3%	48.3%	55.0%	73.3%	56.7%	83.3%	83.3%
	2% ≤ NCFB % < 5%	3.3%	11.7%	13.3%	8.3%	16.7%	10.0%	10.0%
	NCFB % ≥ 5%	41.7%	40.0%	31.7%	18.3%	26.7%	6.7%	6.7%

Table 5. Results, in terms of runoffs, obtained in the simulations performed with product inflow profiles that are the sum of a constant and a random noise, with different amplitude and filtered with low-pass filter with different cut-off frequency.

	Strategy	A		B		C		D
Co-current flow	Buffer	No	Yes	No	Yes	No	Yes	Yes
Co-current flow	Strategy	A		B		C		D
	Buffer	No	Yes	No	Yes	No	Yes	Yes
	Mean value	1.03	0.43	0.67	0.73	0.41	0.08	0.07
	Maximum value	3.47	2.11	2.65	1.97	1.67	0.77	0.71
	0% ≤ runoff % < 2%	81.7%	98.3%	90.0%	100.0%	100.0%	100.0%	100.0%
	2% ≤ runoff % < 5%	18.3%	1.7%	10.0%	0.0%	0.0%	0.0%	0.0%
	Runoff % ≥ 5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Counter-current flow	Mean value	4.23	2.61	0.48	0.41	0.22	0.04	0.04
	Maximum value	12.48	8.93	2.57	1.88	1.67	0.74	0.69
	0% ≤ runoff % < 2%	65.0%	65.0%	95.0%	100.0%	100.0%	100.0%	100.0%
	2% ≤ runoff % < 5%	1.7%	3.3%	5.0%	0.0%	0.0%	0.0%	0.0%
	Runoff % ≥ 5%	33.3%	31.7%	0.0%	0.0%	0.0%	0.0%	0.0%

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Because however the study has evidenced several other characteristics that cannot be directly inferred only from Tables 2–5, the main findings that this study has highlighted for the different pick-and-place strategies and for the different possible plant layouts are concisely described in the following paragraphs. For each strategy, the case in which no buffer is available is analysed first, whereas the case with buffer is considered in a second stage.

Strategy A. (No assignment at all)

This is the less performing strategy. In the co-current setting with no buffer, the workload of the different robotic cells is very unbalanced, leading to an unsafe ageing of the plant, which can reduce its reliability. Practically, the first robot is saturated and works at its maximum speed, whereas the last one is idle or performs few pick-and-place cycles per minute because it does not receive units of product or does not have empty places in the boxes where to place them. In Figure 4a, the graph of the product inflow together with the workload of the different robotic cells is reported for the quite demanding case in which the product unit inflow is constituted by a constant equal to 90% of Q_{max} plus a sinusoid of amplitude equal to 25% of Q_{max} and 1 min period. **F4**

In the counter-current setting, the performances are more satisfactory with less dropouts and a better distribution of the workload among robots, although there is still a consistent variability in

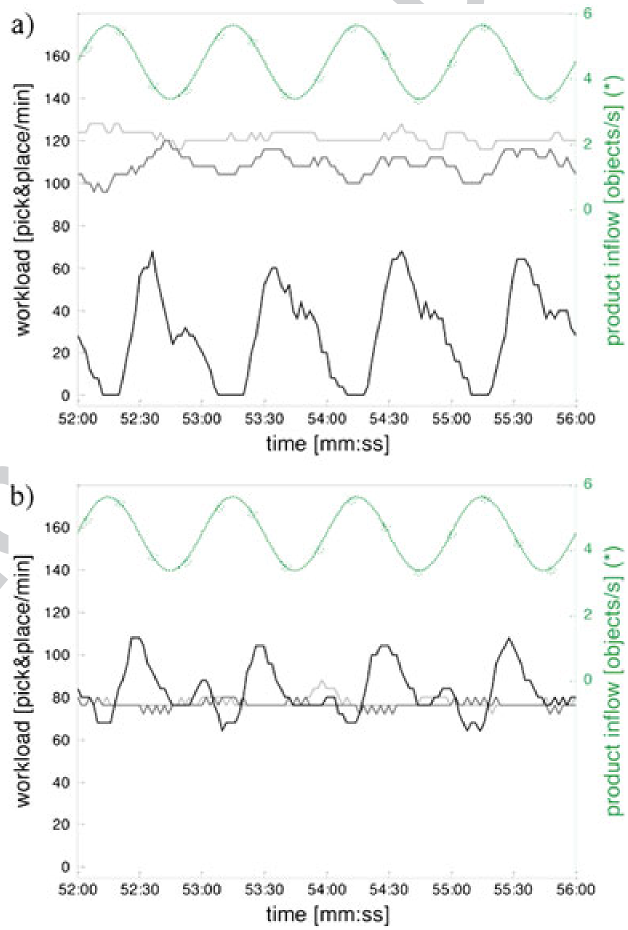

Figure 4. Workload of the first (light grey), second (dark grey) and third robotic cells (black) managing the product inflow (dotted *) with control Strategy A without buffers, in co-current (a) and counter-current (b) flow configurations. The workload of the different robotic cells is very unbalanced.

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time, as evidenced in Figure 4b, which is taken from the simulation with the same inflow as in the previous example. MPEG files S2 and S3, available in the supplementary material online, show the behaviour of the three robotic cells working with strategy A, respectively in co-current and counter-current flow configurations, within the illustrative time interval [53 : 10 53 : 40] – minute : second of simulation.

Considering that the simulated robotic cells can handle about 120 units per minute when they work efficiently, whereas their pick-and-place capability drops to about 80 units per minute when they behave inefficiently picking units that are almost leaving the working area and putting them in empty positions that are also leaving the working area, it can be seen from the figure that the first and second robots work inefficiently at a rather constant low picking rate, whereas the last one switches between the efficient and inefficient conditions in connection with the decrease or the increase of the unit inflow.

The introduction of a buffer in the robotic cells improves the performances of the system in particular in the co-current flow setting. However, the negative features encountered when no buffer is present are still present.

Strategy B. (Incoming units of product are cyclically assigned to the robotic cells)

This strategy consistently improves the performances of the system, in particular in the counter-current setting. As a matter of fact, the equal distribution of the incoming units of product among robotic cells allows them to work in optimal conditions for longer periods of time reducing consistently the eventuality that a cell is overloaded and starts working in inefficient conditions that usually lead to dropouts. The improvement that is obtained in the same case of product inflow as previously, constituted by a constant equal to 90% of $Q_{\max}$ and a sinusoid of amplitude equal to 25% of $Q_{\max}$ and 1 min period, is clearly shown in Figure 5b. From the figure, it can be inferred that the three cells work almost at the same rate. F5

Also, in the co-current flow setting, Strategy B performs quite better than Strategy A. The distribution of units to be picked among robots avoids that the first cells completely fill some boxes that would then cause runoffs when they reach the following robotic cells (as example in MPEG file S2 at 53 : 35 time instant). In Figure 5a, the workload of the robots is reported for the same previously mentioned representative simulation. Also, with this second strategy, the introduction of a buffer in the robotic cells improves the performances of the system in particular in the co-current flow setting. However, it happens that at the very beginning of the simulation, the robots that first receive the empty boxes to be filled (first and second cells in co-current flow setting; second and third cells in counter-current flow setting) empty their buffers because they have plenty of places to fill with the available units. Such buffers remain then empty throughout the simulation, and only the last buffer is actually used by the last robot, as shown in Figure 6a and MPEG file S4, movie of the time interval [53 : 10 53 : 40] – minute : second of the co-current flow simulation performed with the above parameters. F6

Strategy C. (Incoming units of product as well as empty places in the boxes are cyclically assigned to the robotic cells)

This strategy further improves the performances of the plant, in particular in the case in which buffers are available. Indeed, the double assignment of units of product and of empty places to the different robotic cells strongly reduces the phenomenon of unbalanced use of the buffers. In Figure 6b, the time course of the number of object parked on the buffers is reported during a simulation, performed with co-current flow configuration and Strategy C, in which the product unit inflow is constituted by a constant equal to 90% of $Q_{\max}$ and a sinusoid of amplitude equal to 15% of $Q_{\max}$ and 4 min period. MPEG file S5 contains the movie of the simulation during a representative time interval of this simulation ([47 : 20 47 : 40] – minute : second).

However, a quite negative feature that arises in these conditions is the fact that the robots often work uselessly at high rate. This is related to the fact that quite often the robots pick a unit of product and put it in the buffer (because there is no place available in the boxes) and immediately

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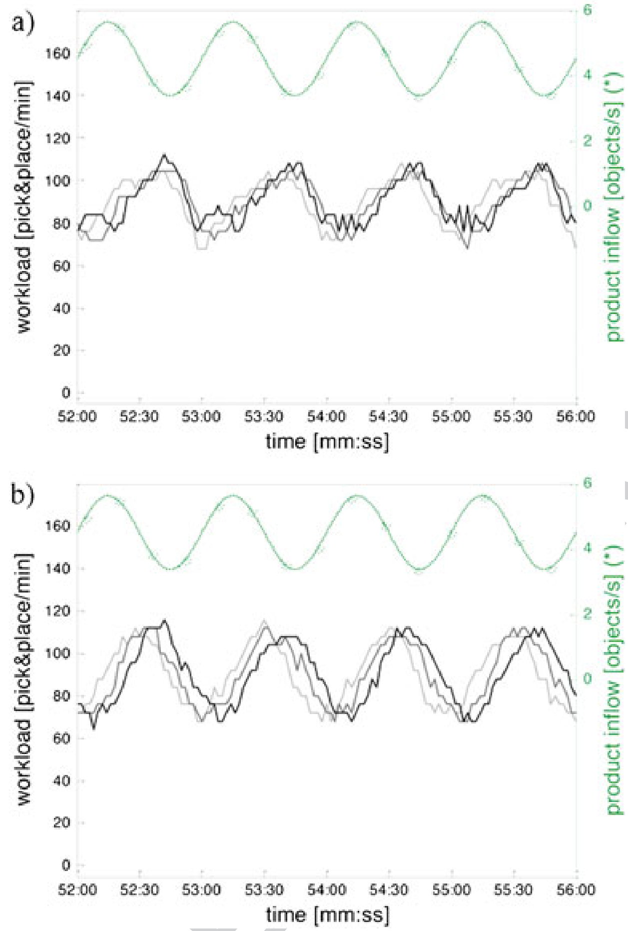

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Figure 5. Workload of the first (light grey), second (dark grey) and third robotic cells (black) managing the product inflow (dotted *) with control Strategy B without buffers, in co-current (a) and counter-current (b) flow configurations. The workload of the different robotic cells is more balanced.

after they pick it from the buffer (because no new unit is available on the conveyor belt) and put it in an empty position that just entered their working space. Such double cycles are clearly not desirable because they overload the robots. This kind of working condition is represented both in Figure 7a and MPEG file S5 [at 47 : 24 time], where it is possible to evince that movements from the belt to the shelf and from the shelf to the boxes occur almost at the same time. **F7**

Strategy D. (Incoming units of product as well as empty places in the boxes are cyclically assigned to the robotic cells, but belt-to-buffer and buffer-to-box cycles are executed only if the unit to be picked or the empty place in the boxes is in the second half of the working space of the robot)

This is the best performing strategy among all those considered in this study: the problem of useless double belt-to-buffer and buffer-to-box cycles is almost eliminated. As represented in Figures 6c and 7b, the different robotic cells work in a rather decoupled way and can deal with consistent variations of the product inflow. Simulation movies of the plant working with co-current and counter-current flow configurations and Strategy D (with the product unit inflow constituted by a constant equal to 90% of Q_{max} and a sinusoid of amplitude equal to 15% of Q_{max} and 4 min period) are reported in MPEG files S6 and S7, respectively.

It is important to underline that with this strategy, the performances that can be obtained with the co-current flow setting are practically equal to those that are obtained with the counter-current flow

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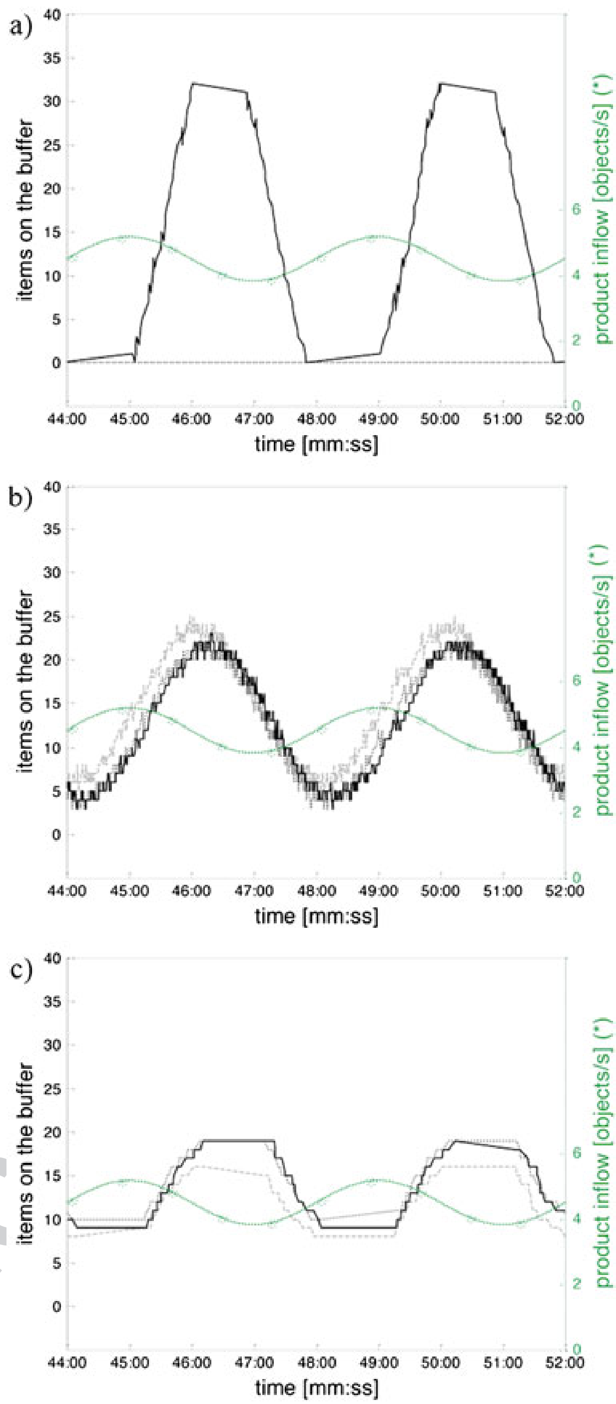

Figure 6. Objects on the buffer of the first (dashed light grey), second (dotted dark grey) and third robotic cells (solid black) managing the product inflow (dotted *) in co-current flow configuration. Adopting control Strategy B, only the third buffer is utilized (a), whereas with control Strategy C, all the buffers are equally used (b). With control Strategy D (c), the improper use of the buffers is eliminated.

setting. On top of this, the co-current flow setting has the advantage that it can handle higher maximum inflow of products without switching to a less efficient working condition as it happens with the counter-current flow setting.

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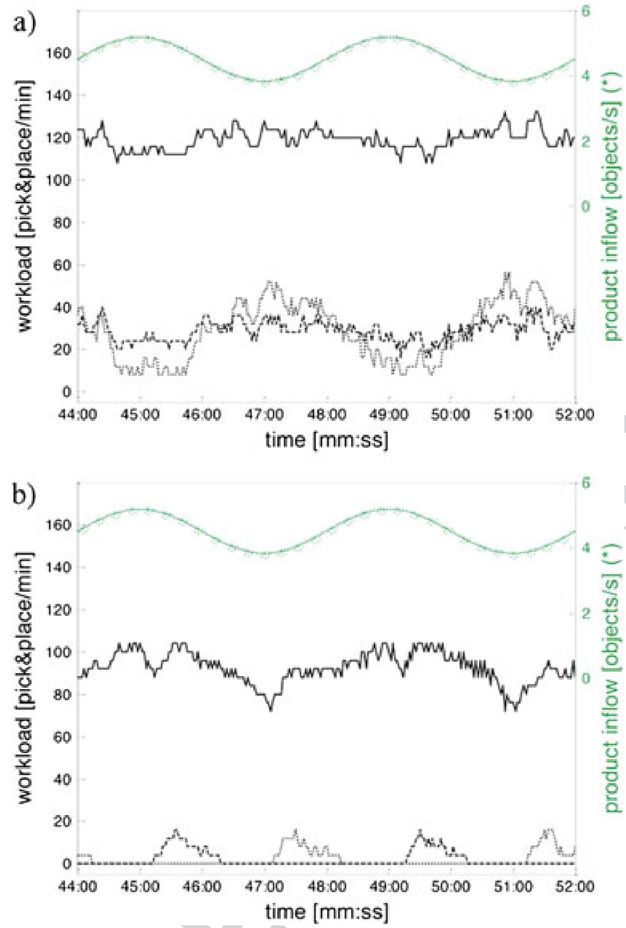

Figure 7. Total workload of the first robotic cell (solid line) managing the product inflow (dotted *) in co-current flow configuration with buffers. Partial workload: quantity of pick-and-place cycles per minute performed to move objects from the inflow conveyor belt to the buffers (dashed line) and from the buffers to the boxes (dotted line), with control strategy C (a) and D (b).

CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

The performances of co-current and counter-current secondary packaging plants have been analysed adopting different settings. Against the common thinking of many packaging plant designers, which consider counter-current configuration the only viable solution to face product-boxes unbalanced perturbations, this paper has clearly shown that it is possible to obtain very good performances with both settings if a proper pick-and-place strategy is chosen as described in the paper. This analysis is of particular practical interest because there is a patent related to the counter-current setting that prevents unauthorized adoption of this configuration. Performances have been shown to be further upgradeable if suitable buffers are accommodated in the robotic cells. The robots can use these buffers to store (or to pick) units of product whenever there is not a free position available in the boxes (or there is not a product unit available on the conveyor belt).

Results have been obtained using a simulator, developed for this purpose, which has been also presented in this paper. It has proved to be a flexible tool for analysing the behaviour of secondary packaging plants for which a meaningful description in terms of their dynamic equations is out of reach. The simulator allows setting a very consistent amount of parameters that practically allow to model a huge number of different possible plants, helping packaging plant designer to chose the best solutions.

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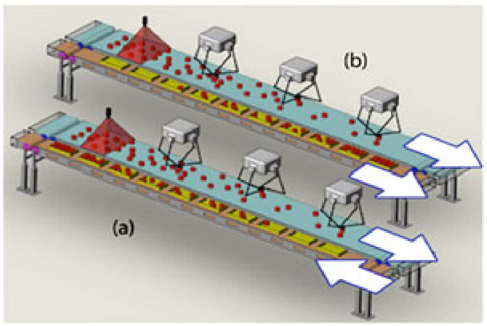
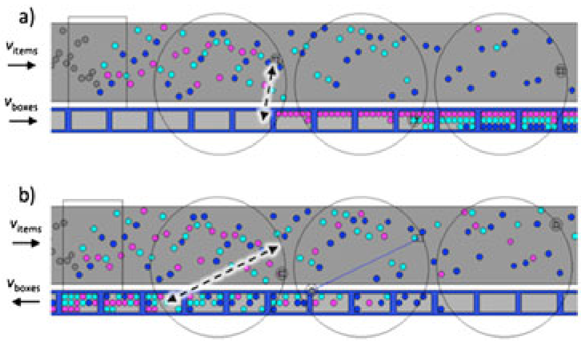
Lorenzo Comba, Gustavo Belforte and Paolo Gay





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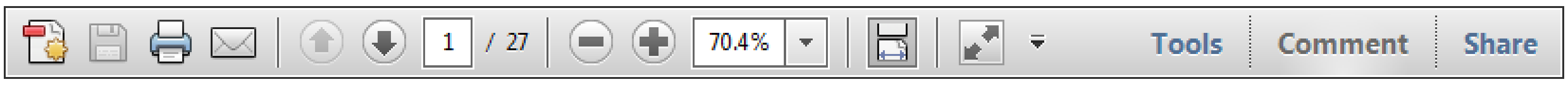

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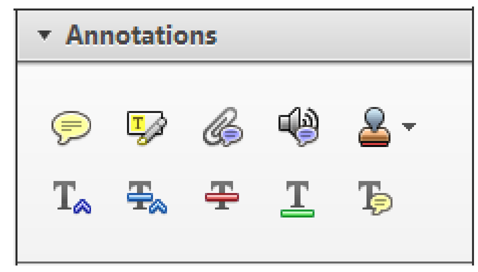

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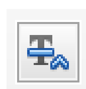

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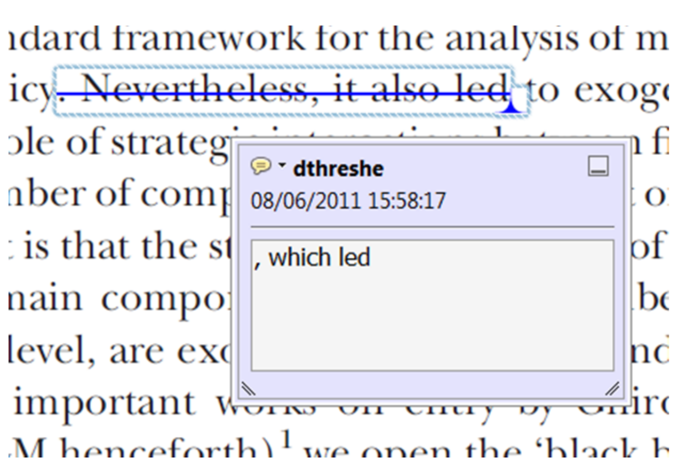

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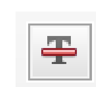

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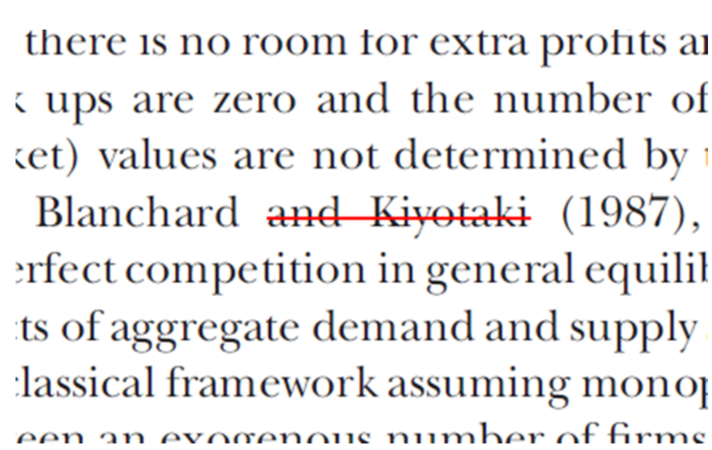

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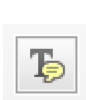

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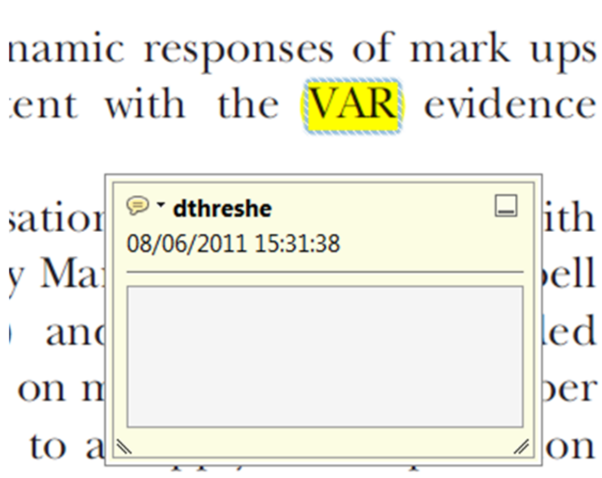

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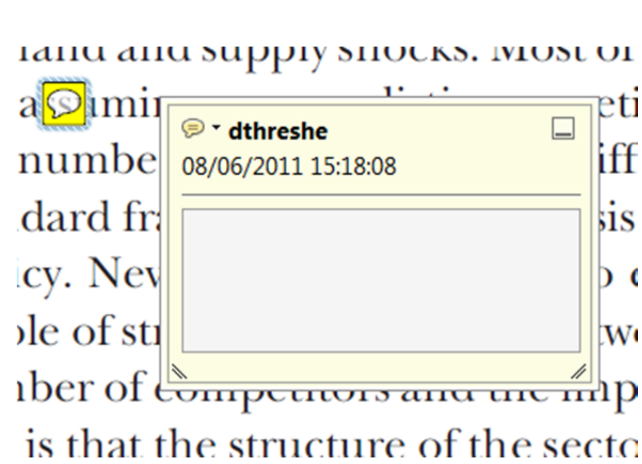

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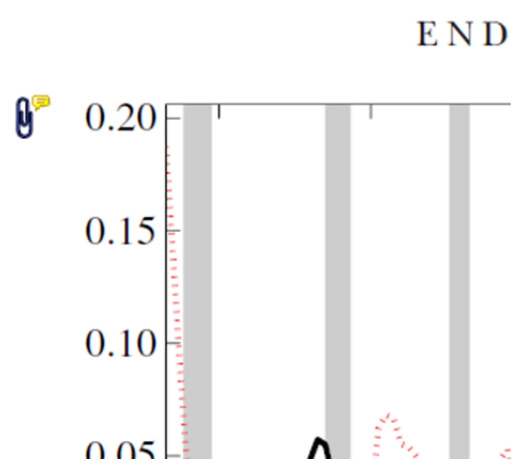

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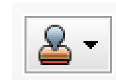

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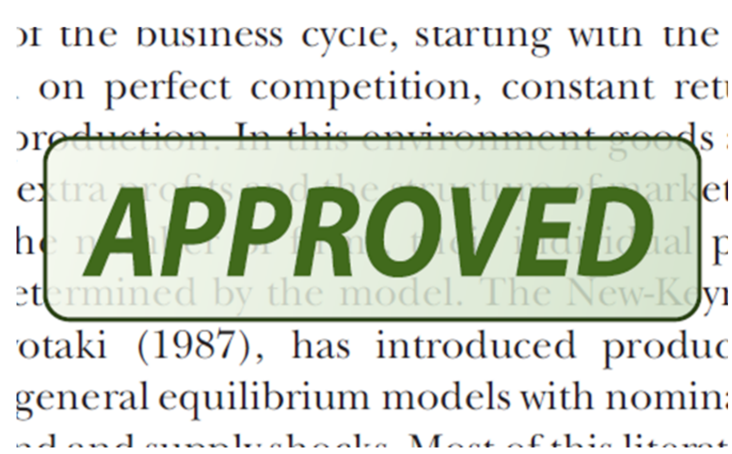

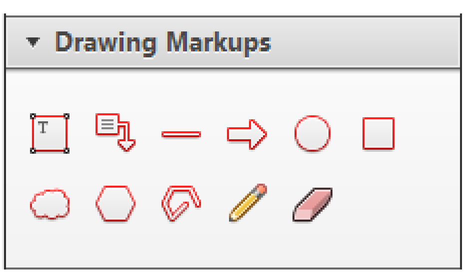

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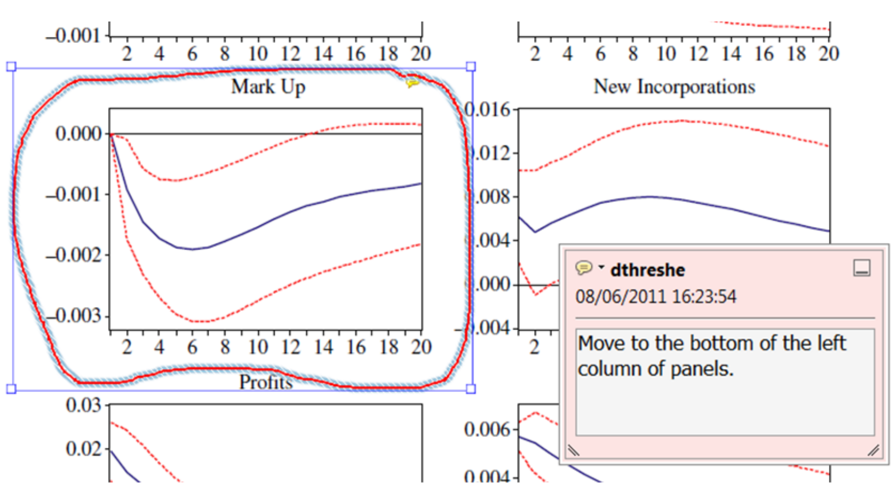

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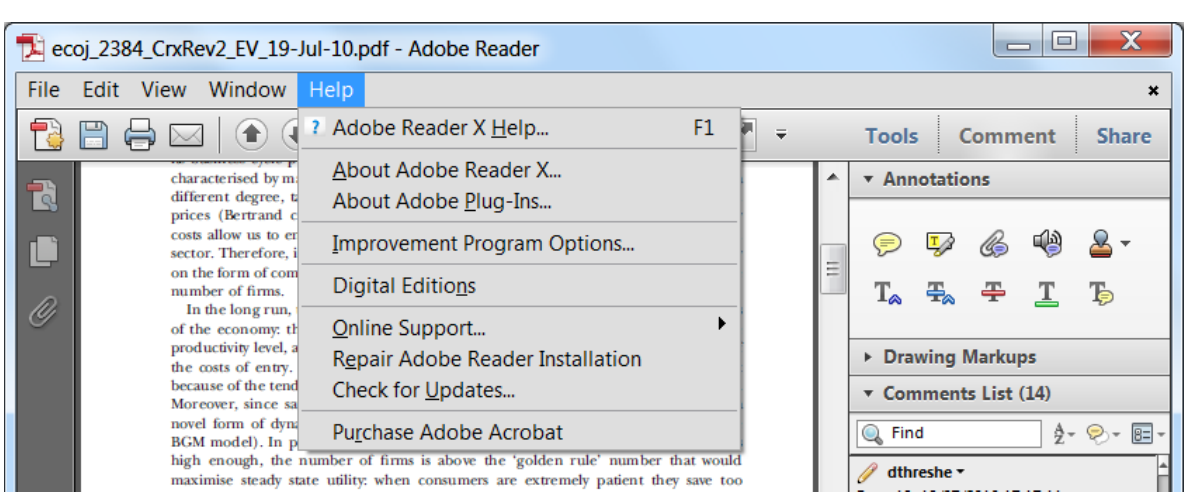

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