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Analysis of an automobile assembly line as a network of closed loops working in both, stationary and transitory regimes

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Abstract

In this work a real automobile assembly line and the correspondent preassembly lines have been analyzed as a network of closed loops of machines decoupled by intermediate buffers. This work deals with some important aspects, which have still not been investigated in earlier literature, such as: machines processing pallets, which are not related to each other and depend on an external variable in a network with closed loops of machines and intermediate buffers, machines working at different cycle times in a network of closed loops of machines and intermediate buffers, machines working in both, stationary and transitory regime and the relationships between the cycle times of the machines in the stationary working regime in order to guarantee the production rate of the system. Finally how the transient results can be used to improve the performance of the system under certain working conditions is discussed.

Keywords: Automobile assembly and preassembly lines; Closed loops.

1. Introduction

This work deals with the analysis of a real automobile assembly line and the different preassembly lines as a network of four closed loops of machines and intermediate buffers, which reflects one of the most common configurations of the automobile assembly and preassembly lines. Although the serial transfer lines formed by machines decoupled by intermediate buffers have been widely investigated (Gershwin 1987, Dallery *et al.* 1992, Tempelmeier *et al.* 2001, Levantesi *et al.* 2003), relatively little research has been done on closed loops of unreliable machines and finite buffers.

Kouikoglou (2002) presents a model of assembly and disassembly production networks based on the first continuous flow simulator applied by D'Angelo *et al.* (1998) in which the traffic of discrete parts is approximated by a continuous flow. However, this model does not consider the phenomena of blocking and starvation transmission in networks formed by several closed loops.

Onvural *et al.* (1990) prove that the production rate of a closed loop depends on the population of pallets that exists in the system due to the transmission of blocking and starvation into the loop.

Frein *et al.* (1996) proposed the first analytical method for evaluating the performance of closed loop systems with unreliable machines and finite buffers. Nevertheless, this method does not consider the correlation existing between the number of parts in the different intermediate buffers and the propagation of the blocking and the starvation on each machine. Gershwin *et al.* (2001) and Werner (2001) handle the decomposition of the closed loop in a similar way to those used for the evaluation of serial transfer lines.

Levantesi (2001) extends the decomposition techniques to the analysis of networks closed loops of unreliable machines and finite intermediate buffers with multiple loops. However, these techniques do not tackle machines processing pallets not univocally related to each other or buffers formed by conveyors.

Maggio *et al.* (2003) present an analytical method for predicting the average production rate and the work in progress in each intermediate buffer in a closed loop of three machines and Gerswhin *et al.* (2003)

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extend this analytical method to simple closed loops with more than three machines, but they do not deal with the analysis of networks formed by several closed loops of machines and intermediate buffers.

Paik *et al.* (2002) propose some decomposition and aggregation methods for finite-buffered one closed-loop production system with unreliable machines and exponentially distributed processing times. However, they do not consider the analysis of networks of closed loops of buffers and machines processing pallets not univocally related to each other, which are common in most automobile assembly lines.

Bastani (1988) studied a closed-loop conveyor with multiple unloading stations and provided an analytical solution to measure the effect of recirculation times, so that loads that find no idle unloading stations, are assumed to recirculate on the conveyor, which is not the case in most automobile assembly lines.

Bozer *et al.* (2004, 2005) model a conveyor as a unidirectional closed-loop consisting of discrete spaces or windows of equal size, which hold at most one load or unit. However, the windows of most conveyors in the automobile industry can vary their size in different branches according to the cycle times of their downstream machines and the transportation speed of the conveyor in each branch. They consider that the different machines are located around the conveyor with a pair of unloading and loading stations per machine, modelling them as output and input queues. However, in the automobile assembly and preassembly lines most machines are formed by conveyors, which are integrated in the closed loop. Thus, in these kinds of assembly lines there is not a pair of loading and unloading stations between each machine and the closed-loop conveyor and they can not be modelled as input and output queues.

This work extends the analysis of networks of closed loops to machines which process pallets not univocally related to each other. In the existing literature, the population, i.e. the sum of pallets, which exist in the intermediate buffers, remain constant at any time in each closed loop. In case of automobile assembly line and the different preassembly lines analyzed, the population of one loop depends on an external variable defined by the ratio of four-door cars (x), placed between the doors disassembly stations from the car body, located in the first branch of the main assembly line and the doors assembly stations in the car body, located in the second branch of the main assembly line. As a consequence of this, the blocking and starvation conditions depend on this variable.

Most automobile assembly and preassembly lines are decoupled by intermediate buffers formed by linear conveyors along which the transport and assembly pallets move from one line to the other at a steady speed. Although closed-loop conveyors have been modelled by some authors (Bastani (1988), Paik *et al.* (2002), Bozer *et al.* (2004, 2005)), no analytical model has been extended to networks with more than one closed-loop conveyor. Thus, this work tackles the analysis of the automobile assembly and preassembly lines as a network of machines and intermediate buffers decoupled by intermediate buffers formed by linear conveyors, differentiating between stationary and transitory working regimes in each machine.

In the stationary working regime the different machines are continuously fed by the upstream buffers with the corresponding transport and assembly pallets at a rate governed by the cycle time of the machine. Due to this fact a minimum number of transport and assembly pallets are necessary in each intermediate buffer in order to guarantee a stationary working regime in the downstream machines at a certain cycle time. These minimum numbers of transport and assembly pallets in each intermediate buffer depend on different factors, such as: the length of the conveyor in the intermediate buffer, the speed of the transport and assembly pallet in the intermediate buffer or the cycle time of the downstream machine, among others.

In the transitory regime the number of transport and assembly pallets in any intermediate buffer can be lower than the minimum one required to guarantee a stationary working regime of the downstream machine at a cycle time. In this case, the cycle time of the downstream machine is higher than the cycle time in the stationary regime and it can be divided into two different cycle times, which correspond to the cycle time of the stationary working regime and to the waiting time for the next transport and assembly pallet to be processed.

In the case of most assembly and preassembly lines, their cycle times under usual working conditions, i.e. in the stationary working regime, differ from each other and they are related to the cycle time of the last branch of the main assembly line in order to guarantee a certain production rate. Thus, this work analyzes

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the relationships between cycle times of the different preassembly and assembly lines under usual working conditions depending on their availability and the ratio of four-door cars to be produced. Finally, the utility of the transient results to determine the optimal configuration of the system under certain conditions is discussed.

2. Description of the network of four closed loops defined by the main assembly and the preassembly lines

This section tackles the description of a network of four closed loops of machines and intermediate buffers and the equations that define the population existing in each closed loop formed by an existing automobile assembly line and the different preassembly lines.

According to Levantesi (2001), the closed loops of a network are defined by invariant values, i.e. by the sum of the number of transport and assembly pallets stored in each buffer, which remains constant at any time. In the automobile assembly and preassembly lines analyzed there are three kinds of transport and assembly pallets corresponding to the car bodies, the front axles and the doors. Each transport and assembly car body and front axle pallet carries, respectively, one unit per assembled car. However, each transport and assembly door pallet carries a pair of doors, left and right, so that, one door pallet is processed per car in case of a complete production of two-door cars while two door pallets are processed per car in case of a complete production of four-door cars in the main assembly line.

Figure 1 represents the main automobile assembly line and the different modules preassembly lines as a network with four closed loops of machines and intermediate buffers.

The first closed loop is defined by the car body transport and assembly conveyor, i.e. by the machine M_1, which represents the car bodies sequencing store, the machine M_2, which represents the first branch of the main assembly line, the machine M_3, which represents the chassis assembly line, the machine M_4, which represents the second and final branch of the main assembly line and the intermediate buffers $B_{1,2}$, $B_{2,3}$, $B_{3,4}$ and $B_{4,1}$, which decouple the machines M_1, M_2, M_3 and M_4 respectively.

In the second branch of the main assembly line (M_4), which determines the production rate of the system, the car body is transferred from the assembly pallet to a floor conveyor, returning the empty car body transport and assembly pallets to the car bodies sequencing store (M_1). Thus, buffer $B_{1,2}$ transports car bodies to be assembled, buffers $B_{2,3}$, $B_{3,4}$ contain car body assembly pallets in different assembly states, while buffer $B_{4,1}$ carries empty car body transport and assembly pallets. In the car bodies sequencing store (M_1) the car bodies are transferred to the empty pallets coming from the second branch of the main assembly line (M_4).

Figure 1. *Network with four closed loops of machines and intermediate buffers defined by the main assembly line and the preassembly lines analyzed.*

The sum of the number of transport and assembly car body pallets stored at any time in the buffers of the first closed loop, which are represented by $n_{1,2}$, $n_{2,3}$, $n_{3,4}$ and $n_{4,1}$, remains constant and is defined by Equation (1).

$$n_{1,2}+n_{2,3}+n_{3,4}+n_{4,1}=237 \tag{1}$$

The doors disassembly stations, located in the first branch of the main assembly line, which is represented by the machine M_2, the doors preassembly line, which is represented by the machine M_5, the doors inspection line, which is represented by the machine M_6, the doors assembly stations, placed in the second branch of the main assembly line, which is represented by the machine M_4 and the intermediate buffers $B_{2,5}$, $B_{5,6}$, $B_{6,4}$ and $B_{4,2}$, which decouple the machines M_2, M_5, M_6 and M_4, respectively, define the second closed loop, which represents the doors assembly and transport conveyor. Thus, buffer $B_{2,5}$ contains pallets

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with doors to be preassembled, buffers $B_{5,6}$ and $B_{6,4}$ carry pallets in different preassembly states, while buffer $B_{4,2}$ contains empty doors transport and assembly pallets.
The sum of the number of transport and assembly door pallets stored at any time in the buffers of the second closed loop, which are represented by $n_{2,5}$, $n_{5,6}$, $n_{6,4}$ and $n_{4,2}$ respectively, remains constant and is defined by Equation (2).

$$n_{2,5}+n_{5,6}+n_{6,4}+n_{4,2}=450 \quad (2)$$

The third closed loop represents the front axles assembly and transport conveyor, defined by the chassis assembly line (M_3), the front axle preassembly line (M_7), and the intermediate buffers $B_{3,7}$ and $B_{7,3}$, which decouple machines M_3 and M_7, respectively. Thus, buffer $B_{3,7}$ contains empty front axle transport and assembly pallets, while buffer $B_{7,3}$ carries pallets with assembled front axles.
The sum of the number of transport and assembly front axle pallets stored at any time in the buffers of the third closed loop, which are represented by $n_{3,7}$ and $n_{7,3}$, also remains constant according to real values as shown in Equation (3).

$$n_{3,7}+n_{7,3}=138 \quad (3)$$

Because each transport and assembly door pallet carries a pair of doors, left and right, one and two door pallets have to be processed respectively every two and four doors car assembled in the main assembly line. The number of transport and assembly door pallets, which carry doors in different assembling states is equal to the number of car bodies with disassembled doors located in the main assembly line multiplied by (1+x). Taking into account that the sum of the number of transport and assembly door pallets in the doors preassembly and inspection lines remains constant and the sum of car bodies with disassembled doors in the two branches of the main assembly line also remains constant, the fourth closed loop is defined by the governing Equation (4).

$$n_{2,5}+n_{5,6}+n_{6,4}+60 = (216+n_{2,3}+n_{3,4}).(1+x) \quad (4)$$

Where $n_{2,5}$, $n_{5,6}$ and $n_{6,4}$, are the number of transport and assembly door pallets in the corresponding intermediate buffers $B_{2,5}$, $B_{5,6}$ and $B_{6,4}$ and $n_{2,3}$ and $n_{3,4}$ are the number of transport and assembly car body pallets in the intermediate buffers $B_{2,3}$ and $B_{3,4}$.
Notice that the governing equation of the fourth closed loop links the number of transport and assembly door pallets in the buffers $B_{2,5}$, $B_{5,6}$ and $B_{6,4}$ of the second closed loop with the number of transport and assembly car body pallets in the buffers $B_{2,3}$ and $B_{3,4}$ of the first closed loop via an external variable (x), which varies between 0 and 1. The existing literature does not deal with the equations in which the population does not remain constant and depends on an external variable, like Equation (4).
In most automobile assembly and preassembly lines it is necessary to analyze the behaviour of closed loops defined by equations, such as (4), which relates the number of pallets existing in buffers of different closed loops to an external variable (x).

3. Analysis of the blocking and starvation conditions of each machine in the four closed loop network

This section analyzes the blocking and starvation conditions of each machine in the four closed loop network considering that they work at different cycle times and some of them process pallets, which are not univocally related to each other and depend on an external variable, which is usual in most automobile assembly lines.

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In the analysis of serial transfer lines of machines and intermediate buffers with different cycle times, Levantesi *et al.* (2003) consider that an intermediate buffer $B_{i,j}$ can be empty ($n_{i,j}=0$) and the downstream machine M_j can partially starve if its production rate (η_j) is higher than the production rate (η_i) of the upstream machine M_i ($\eta_j>\eta_i$). In the same way, they consider that the downstream machine never starves, even if the intermediate buffer $B_{i,j}$ remains empty ($n_{ij}=0$), if the production rate of the downstream machine (η_j) does not exceed the production rate of the upstream machine (η_i) ($\eta_i\geq\eta_j$),

However, these starvation conditions do not occur in most manufacturing systems, like the automobile assembly and preassembly lines. In these cases, the intermediate buffers ($B_{i,j}$) are formed by linear conveyors of length ($l_{i,j}$) along which the transport and assembly pallets move from one line to the other at a steady speed ($v_{i,j}$). A transport and assembly pallet processed by the upstream machine (M_i) cannot be immediately processed by the downstream machine (M_j) because of the time ($t_{i,j}$), which is needed to transit on the conveyor between machines (M_i) and (M_j).

Therefore the downstream machine (M_j) always starves if the intermediate buffer ($B_{i,j}$) remains empty ($n_{i,j}=0$) regardless of the relationship between the production rates of the upstream and downstream machines. Thus, machines M_1, M_5, M_6 and M_7, fed by one intermediate buffer, starve if their upstream buffers i.e. $B_{4,1}$, $B_{2,5}$, $B_{5,6}$ and $B_{3,7}$ remain empty. In the case of the machines fed by two intermediate buffers, i.e. M_2, fed by $B_{1,2}$ and $B_{4,2}$, M_3, fed by $B_{2,3}$ and $B_{7,3}$ and M_4, fed by $B_{3,4}$ and $B_{6,4}$, they starve, when at least one of their upstream buffers remain empty.

In the analysis of serial transfer lines of machines and intermediate buffers with different cycle times, Levantesi *et al.* (2003) consider that an intermediate buffer $B_{i,j}$ can be full ($n_{i,j}= n_{i,j\ max.}$) and the upstream machine M_i can be partially blocked if its production rate (η_i) is higher than the production rate (η_j) of the downstream machine M_j ($\eta_i>\eta_j$). In the same way, if the production rate of the upstream machine (η_i) does not exceed the production rate of the downstream machine (η_j) ($\eta_j\geq\eta_i$), the upstream machine is never blocked, even if the intermediate buffer $B_{i,j}$ remains full ($n_{i,j}=n_{i,j\ max.}$).

These blocking conditions go on being valid for those machines, which feed only one buffer in networks of closed loops and process the same amount of assembly and transport pallets per assembled model as their downstream machines. Therefore, machines M_1, M_5 and M_7, which feed one buffer and process the same amount of pallets as their downstream machines (M_2, M_6 and M_3), remain partially blocked if the downstream buffers are full, i.e. $n_{1,2}=n_{1,2\ max.}$ for M_1, $n_{5,6}=n_{5,6\ max.}$ for M_5 and $n_{7,3}=n_{7,3\ max.}$ for M_7, and their production rates are higher than the production rates of the corresponding downstream machines, i.e. $\eta_1>\eta_2$ for M_1, $\eta_5>\eta_6$ for M_5 and $\eta_7>\eta_3$ for M_7.

However, these blocking conditions are not valid for those machines which feed more than one buffer or process different amounts of assembly and transport pallets per assembled model than their downstream machines, which is the usual procedure in most automobile assembly and preassembly lines.

In the case of machines which feed two intermediate buffers and process the same amount of assembly and transport pallets per car than their downstream machines, i.e. the machine M_3, which feeds buffers $B_{3,4}$ and $B_{3,7}$ and the machine M_4, which feeds buffers $B_{4,1}$ and $B_{4,2}$, they remain partially blocked if at least one of their downstream buffers is full and the production rate of the upstream machine is higher than the production rate of the downstream machine, i.e. the machine M_3 remains partially blocked if $n_{3,4}=n_{3,4\ max.}$ and $\eta_3>\eta_4$ or $n_{3,7}=n_{3,7\ max.}$ and $\eta_3>\eta_7$ and the machine M_4 remains partially blocked if $n_{4,1}=n_{4,1\ max.}$ and $\eta_4>\eta_1$ or $n_{4,2}=n_{4,2\ max.}$ and $\eta_4>\eta_2$.

In the case of machine M_6, which processes (1+x) door transport and assembly pallets per each assembled car in the second branch of the main assembly line (M_4), it remains partially blocked if the downstream buffer $B_{6,4}$ is full, i.e. $n_{6,4}=n_{6,4\ max.}$, and its production rate is higher than the production rate of the corresponding downstream machine M_4, multiplied by (1+x), i.e. $\eta_6>\eta_4.(1+x)$. Machine M_2 feeds two intermediate buffers $B_{2,5}$ and $B_{2,3}$ and one of its downstream machines (M_5) processes (1+x) door transportation and assembling pallets per each car assembled in M_2, hence machine M_2 remains blocked if $n_{2,5}=n_{2,5\ max.}$ and $\eta_2.(1+x)>\eta_5$ or $n_{2,3}=n_{2,3\ max.}$ and $\eta_2>\eta_3$.

Table 1. shows the blocking and the starvation conditions in each machine of the four closed loops.

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4. Analysis of the cycle times of the machines working in both, stationary and transitory regimes

This section tackles the analysis of the cycle times of the main automobile assembly line and the different preassembly lines taking into consideration that the intermediate buffers are formed by linear conveyors. The existing literature does not analyze the existence of dynamic intermediate buffers in networks of several closed loops formed by linear conveyors. Due to the lack of research in this field and the significance of the buffers formed by linear conveyors in most automobile assembly lines, it is necessary to distinguish between stationary and transitory working regimes in the machines forming the network of closed loops.

The stationary working regime is characterized by a continuous feeding of the machines with transport and assembly pallets, therefore the minimum contents of the intermediate buffer $B_{i,j}$ required for a stationary working regime of its downstream machine M_j is defined by the minimum number of transport and assembly pallets in this buffer required to guarantee a continuous feeding of the downstream machine M_j. The minimum contents ($n_{i,j\ min}$) of every intermediate buffer ($B_{i,j}$) required for a stationary working regime of their downstream machines, except for the buffers $B_{4,2}$ and $B_{6,4}$, depend on: the cycle times in stationary regime (c_{js}) of the downstream machines, the length ($l_{i,j}$) of the intermediate buffers and the transportation speed ($v_{i,j}$) of the assembling pallets, as Equation (5) shows.

For $n_{1,2}$, $n_{2,3}$, $n_{3,4}$, $n_{4,1}$, $n_{2,5}$, $n_{5,6}$, $n_{3,7}$ and $n_{7,3}$ $$n_{i,j,\ min} = l_{i,j}/(c_{js}.v_{i,j}) \quad (5)$$

Due to the fact that intermediate buffers $B_{4,2}$ and $B_{6,4}$ store door transport and assembly pallets and their downstream machines M_2 and M_4 process car bodies, each car body requires 1+x door transport and assembly pallets in the stations for disassembling and assembling the doors. Therefore, the minimum contents ($n_{i,j\ min}$) of the intermediate buffers $B_{4,2}$ and $B_{6,4}$, required for the stationary working regimes of their downstream machines, depend on: the cycle times in stationary regime (c_{js}) of the downstream machines, the length ($l_{i,j}$) of the intermediate buffers, the transportation speed ($v_{i,j}$) of the assembling pallets and they also depend on x, as is shown by Equation (6).

For $n_{6,4}$ and $n_{4,2}$ $$n_{i,j,\ min} = l_{i,j}.(1+x)/(c_{js}.v_{i,j}) \quad (6)$$

The maximum capacity ($n_{i,j\ max}$) of each intermediate buffer $B_{i,j}$ depends on the ratio between the length of the conveyors ($l_{i,j}$) and the average storing length per transport and assembly pallet ($l_{aspi,j}$), as Equation (7) shows.

$$n_{i,j,\ max} = l_{i,j}/l_{aspi,j} \quad (7)$$

The transitory working regime is characterized by a discontinuous feeding of the machines with transport and assembly pallets, hence the number of transport and assembly pallets ($n_{i,j}$), which exists in each intermediate buffer $B_{i,j}$ for a transitory working regime of their downstream machines (M_j), is defined by Equations (8) and (9).

For $n_{1,2}$, $n_{2,3}$, $n_{3,4}$, $n_{4,1}$, $n_{2,5}$, $n_{5,6}$, $n_{3,7}$ and $n_{7,3}$ $$0<n_{i,j}<n_{i,j,\ min} = l_{i,j}/(c_{js}.v_{i,j}) \quad (8)$$

For $n_{6,4}$ and $n_{4,2}$ $$0<n_{i,j}<n_{i,j,\ min}=l_{i,j}.(1+x)/(c_{js}.v_{i,j}) \quad (9)$$

The cycle times of machines M_1, M_5, M_6 and M_7 fed by one intermediate buffer, which work in transitory (c_{jt}) and stationary (c_{js}) regimes are defined by Equations (10) and (11) respectively, if they suffer neither a starvation from their upstream buffers ($B_{i,j}$) nor a blockage from their downstream buffers ($B_{j,k}$). Notice that Equation (11) is directly deduced from Equation (5).

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For c_{1t}, c_{5t}, c_{6t} and c_{7t}. If $0<n_{i,j}<n_{i,j,\,min}$ $\quad c_{jt}=l_{i,j}/(n_{i,j}.\ v_{i,j})$ (10)

For c_{1s}, c_{5s}, c_{6s} and c_{7s}. If $n_{i,j}\geq n_{i,j,\,min}$ $\quad c_{js}=l_{i,j}/(n_{i,j\ min}.v_{i,j})$ (11)

In case of machines (M_j) fed by two intermediate buffers, i.e. M_2 fed by $B_{1,2}$ and $B_{4,2}$, M_3 fed by $B_{2,3}$ and $B_{7,3}$ and M_4 fed by $B_{3,4}$ and $B_{6,4}$, their cycle times in transitory regime (c_{jt}) are determined by the intermediate buffer, which feeds them at a lower frequency, as is shown by Equations (12), (13) and (14), respectively, if they suffer neither a starvation from their upstream buffers ($B_{i1,j}$ or $B_{i2,j}$) nor a blockage from their downstream buffers ($B_{j,k1}$ or $B_{j,k2}$).

If $0<n_{1,2}<n_{1,2\ min.}$ or $0<n_{4,2}<n_{4,2\ min.}$

$$c_{2t}=\max\begin{cases}\dfrac{l_{1,2}}{n_{1,2}.v_{1,2}}\\[2ex]\dfrac{l_{4,2}.(1+x)}{n_{4,2}.v_{4,2}}\end{cases} \tag{12}$$

If $0<n_{2,3}<n_{2,3\ min.}$ or $0<n_{7,3}< n_{7,3\ min.}$

$$c_{3t}=\max\begin{cases}\dfrac{l_{2,3}}{n_{2,3}.v_{2,3}}\\[2ex]\dfrac{l_{7,3}}{n_{7,3}.v_{7,3}}\end{cases} \tag{13}$$

If $0<n_{3,4}<n_{3,4\ min.}$ or $0<n_{6,4}<n_{6,4\ min.}$

$$c_{4t}=\max\begin{cases}\dfrac{l_{3,4}}{n_{3,4}.v_{3,4}}\\[2ex]\dfrac{l_{6,4}.(1+x)}{n_{6,4}.v_{6,4}}\end{cases} \tag{14}$$

Machines M_2, M_3 and M_4 and the intermediate buffers of the first closed loop $B_{1,2}$, $B_{2,3}$, $B_{3,4}$ and $B_{4,1}$ are power-and-free chain conveyors. However, machines M_5, M_6 and M_7 and the intermediate buffers $B_{2,5}$, $B_{5,6}$, $B_{6,4}$, $B_{4,2}$, $B_{3,7}$ and $B_{7,3}$ are electrical monorail conveyors. In both cases, the conveyors might not maintain a fixed distance in the intermediate buffers. Meanwhile, they must keep a fixed distance in the branches of the main assembly line and the different preassembly lines, represented by machines M_2 to M_7. If conveyors do not keep a fixed distance in the intermediate buffers and they are set very fast, the cycle time of their downstream machines and the time spent in the transient regime would be reduced according to Equations (10), (12), (13) and (14).

The cycle times in stationary regime (c_{js}) of the machines (M_j) fed by two intermediate buffers are shown by Equations 15, 16 and 17, respectively, and they remain constant if the number of pallets existing in both upstream buffers is at least equal to the value of the minimum contents ($n_{i,j\ min}$) of every intermediate buffer ($B_{i,j}$), which is required for a stationary working regime of their downstream machines, as shown by Equations (5) and (6), and they do not remain blocked by their downstream buffers according to the blocking conditions expressed in Table 1.

For $n_{1,2}\geq n_{1,2\ min.}$ and $n_{4,2}\geq n_{4,2\ min.}$ $\quad c_{2s}=l_{1,2}/(n_{1,2\ min.}.v_{1,2})=l_{4,2}.(1+x)/(n_{4,2\ min.}.v_{4,2})$ (15)

For $n_{2,3}\geq n_{2,3\ min.}$ and $n_{7,3}\geq n_{7,3\ min.}$ $\quad c_{3s}=l_{2,3}/(n_{2,3\ min.}.v_{2,3})=l_{7,3}/(n_{7,3\ min.}.v_{7,3})$ (16)

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For $n_{3,4} \geq n_{3,4\ min}$ and $n_{6,4} \geq n_{6,4\ min}$ $$c_{4s}=l_{3,4}/(n_{3,4\ min}.v_{3,4})=l_{6,4}.(1+x)/(n_{6,4\ min}.v_{6,4}) \quad (17)$$

The relationships between the cycle times of machines in networks of closed loops have not yet been analyzed by the existing literature. The cycle times of most assembly and preassembly lines under normal working conditions, i.e. in the stationary working regime, are set up in relation to the cycle time of the machine, which determines the production rate of the system, and they depend on several factors, such as: their availability in stationary regime (A_{is}), the availability of the machine M_4, which fixes the production rate of the whole system (A_{4s}), and a value of the cycle time (x_i) to be reduced in each machine M_i in order to guarantee the production rate of the system in stationary regime. The availabilities of the different machines in the stationary working regime (A_{is}) are determined by their MTBF and MTTR values under normal working conditions, i.e. when the machines are continuously fed by their upstream buffers. Notice that the availabilities in the transitory working regime (A_{it}) differ from those in stationary working regime (A_{is}) due to the different MTBF and MTTR values because machines are uncontinuously fed by their upstream buffers and they have to stop while they are waiting for the next pallet to be processed.

In the case of the main automobile assembly line and the different preassembly lines analyzed, the production rate of the system is determined by the cycle time of the second branch of the main assembly line, represented by the machine M_4.

In this sense it is necessary to differentiate between machines, which process pallets univocally and not univocally related with car body transport and assembly pallets.

The cycle times of machines, which process transport and assembly pallets univocally related with the car body transport and assembly pallets, i.e. machines M_1, M_2, M_3 and M_7, are related in stationary regime with the cycle time of machine M_4 according to Equation (18).

For c_{1s}, c_{2s}, c_{3s} and c_{7s} $$c_{is}=c_{4s}.(A_{is}/A_{4s})- x_i \quad (18)$$

The cycle times of machines, which process transport and assembly pallets not univocally related with the car body transport and assembly pallets, i.e. machines M_5 and M_6, which process door transport and assembly pallets, are related in stationary regime with the cycle time of machine M_4, as is shown by Equation (19).

For c_{5e} and c_{6e}. $$c_{is} = \frac{c_{4s}.\frac{A_{is}}{A_{4s}} - x_i}{(1+x')} \quad (19)$$

Notice that the cycle times in stationary regime of the doors preassembly (M_5) and inspection lines (M_6), according to Equation (19) are adjusted according to the ratio of four doors cars to be produced during a certain period of time (x'), which differs from the fourdoor cars ratio (x), at a instant of time, placed between the doors disassembly stations from the car body, located in M_2, and the doors assembly stations in the car body, located in M_4.

As a consequence of machines M_1, M_2, M_4, M_5, M_6 and M_7 are formed by similar linear conveyors, their availabilities under normal working conditions, i.e. in stationary regime, are identical. However, the availability of the chassis assembly line, represented by the machine M_3, reaches 85% of the availability of the reference machine M_4, due to its higher level of automation in comparison with the level of automation of the reference machine M_4.

Considering that the ratio of fourdoor cars to be produced is x=0.7, the values of the cycle times x_i to be reduced in each machine are equal to 0.01 for machines M_1 and M_2, equal to 0.02 for machines M_5, M_6 and M_7 and equal to 0 for machine M_3, respectively, and the cycle time of machine M_4 in stationary regime (c_{4s}) is equal to 1.08 min./pallet, which correspond to real values, the cycle times of the different machines in stationary regime are represented in Table (2), according to Equations (18) and (19).

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Table 3 represents the lengths of conveyors ($l_{i,j}$), the average storing length per transport and assembly pallet ($l_{aspi,j}$) and the transport speed ($v_{i,j}$) of assembly pallets in each intermediate buffer ($B_{i,j}$).

Table 4 represents the minimum contents ($n_{i,j\ min}$) of each intermediate buffer ($B_{i,j}$) required for the stationary working regime of their downstream machines, which have been calculated according to: Equations (5) and (6), the values of Table (2), the lengths of conveyors ($l_{i,j}$) and the transport speed ($v_{i,j}$) of the assembly pallets in each intermediate buffer ($B_{i,j}$), represented in Table (3), and the maximum capacities in both working regimes ($n_{i,j\ max}$).

Due to the fact that most buffers are formed by conveyors, which cannot vary their length or the transport speed of the pallets easily, the values of minimum contents ($n_{i,j\ min}$) represented in Table (4) depend really on the values of cycle times of their downstream machines in stationary regime (c_{js}). In the case of increasing the production rate of the system, which means decreasing the cycle time of the governing machine M_4 and its related machines, the values of minimum contents increase, i.e. as the production rates of machines increase, they require a higher number of pallets in their upstream buffers to guarantee their production rates.

Because buffers $B_{6,4}$ and $B_{4,2}$ contain doors transport and assembly pallets and their downstream machines (M_4 and M_2) process car body transport and assembly pallets, which are not univocally related to each other, their minimum contents ($n_{6,4\ min}$ and $n_{4,2\ min}$) required for the stationary working regime of their downstream machines also depend on the fourdoor cars ratio (x).

Notice that the maximum contents ($n_{i,j\ max}$) of the intermediate buffers are determined by their storage capacity, represented by the ratio between the length of the conveyor ($l_{i,j}$) and the average storing length ($l_{aspi,j}$) per pallet, according to Equation (7), and they do not depend on the working regimes of the downstream machines. In the transitory regime the different machines work at a cycle time higher than the cycle time at stationary regime. The transient results are very useful and can be used in case of disruption of any machine of the four closed loops. Whenever one machine is disrupted, the numbers of pallets in its downstream buffers tend to reach their minimum values. Hence, if any machine of the closed loops has a disruption, its downstream machines tend to work in transitory regime. In this case, once any machine stops, the numbers of pallets in its downstream buffers tend to zero. Thus, the transient results can be used to maximize the time between the disruption of any machine of the closed loops and the blockage or starvation of machine M_4, which determines the production rate of the entire system, maximizing so the units produced by the assembly line.

The transient results can be used to determine the optimal size of the buffers and the number of pallets in case of disruption of any machine of the closed loops. In this case, depending on the values of the variable x, the time between the disruption of one machine of the closed loops and the blockage of the second and the last branch of the main assembly line (M_4) depends on the size of the buffers. By modifying the size of the buffers and the number of pallets, the units produced by the assembly line can be maximized after a disruption of one machine of the closed loops.

By using this methodology, the conveyor speeds of the intermediate buffers after disruption of one machine of the closed loops can be determined. Moreover, the fraction of time that the machines are in the transient state can be modified with the main aim of maximizing the production.

Figure 2 represents the relationship between the cycle time in transitory (c_{1t}) and stationary (c_{1s}) regimes in the car bodies sequencing store (M_1), and the number of pallets existing in its upstream buffer ($B_{4,1}$) according to: Equations (10) and (11) for the transitory and stationary working regimes and the values of Tables (3) and (4).

The relationship between the cycle time of machine M_1 in transitory regime (c_{1t}) and the number of pallets ($n_{4,1}$) existing in its upstream buffer ($B_{4,1}$) is shaped like an exponential decay function while $n_{4,1}<n_{4,1\ min}$, i.e. as the number of pallets $n_{4,1}$ increase, the cycle times in transitory regime (c_{1t}) decrease, if machine M_1 does not remain blocked by its downstream buffer $B_{1,2}$.

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In the transitory working regime the cycle time (c_{1t}) is higher than the cycle time in the stationary regime (c_{1s}), which means that machine M_1 in transitory regime works physically at a cycle time, which corresponds to the cycle time of the stationary regime (c_{1s}) and it is waiting during a cycle time (c_{1t}-c_{1s}) for the next transport and assembly pallet to be processed. Notice that, while $n_{4,1}$ increases in the stationary working regime and approaches the minimum contents ($n_{4,1\ min}$), the cycle time in transitory regime (c_{1t}) tends to approximate to the cycle time in stationary regime (c_{1s}) and the waiting cycle time tends to zero.
When the number of pallets, that exists in buffer $B_{4,1}$, reaches its minimum value ($n_{4,1\ min}$=31), according to Table (4), the downstream machine M_1 begins to work in stationary regime at cycle time c_{1s}, which remain constant while the numbers of pallets increase ($n_{4,1} \geq n_{4,1\ min}$).

Figure 2. *Relationships between the cycle times of machine M_1 in transitory (c_{1t}) and stationary regimes (c_{1s}) and the number of pallets existing in its upstream buffer ($n_{4,1}$)*

Figure 3 represents the relationship between the cycle times in the first branch (M_2) of the main automobile assembly line in transitory (c_{2t}) and stationary (c_{2s}) regimes, the numbers of pallets existing in its upstream buffers ($B_{1,2}$ and $B_{4,2}$) and the fourdoors car ratio (x), according to: Equations (12) and (15) for the transitory and stationary working regimes and the values of Tables (3) and (4).
These relationships are valid if machine M_2 does not remain blocked by one of its downstream buffers ($B_{2,5}$ or $B_{2,3}$) according to the blocking conditions expressed in Table 1.
According to Equation (12), the relationship between the cycle time of machine M_2 in transitory regime (c_{2t}) and the numbers of pallets ($n_{1,2}$) is shaped like an exponential decay function, which does not depend on (x), as is shown by the right curve of Figure (3). However, the relationship between the cycle time of machine M_2 in transitory regime (c_{2t}) and the numbers of pallets ($n_{4,2}$), which is also shaped like an exponential decay function, depends on (x) too, as is shown by the left curve of Figure (4). In this case, notice, that $n_{4,2\ min}$ also depends on x.
As a consequence machine M_2 is being fed by two buffers ($B_{1,2}$ and $B_{4,2}$), its cycle time is governed by the upstream buffer, which feeds it at a lower frequency. According to this aspect, if the numbers of pallets existing in both upstream buffers do not reach their minimum values ($n_{1,2}<n_{1,2\ min}$ and $n_{4,2}<n_{4,2\ min}$) the cycle time of the downstream machine M_2 is governed by the buffer, which contributes to a higher value at transitory regime. Equally, if the number of pallets in one of the upstream buffers is at least equal to its minimum value ($n_{j,2} \geq n_{j,2\ min}$) and the number of pallets in the other one does not reach its minimum value ($n_{k,2}<n_{k,2\ min}$), the cycle time of the downstream machine M_2 is governed by buffer $B_{k,2}$, which corresponds a higher cycle time. In the case where the numbers of pallets in both upstream buffers reach their minimum values, according to Table (4) ($n_{1,2} \geq 21$ and $n_{4,2} \geq 8.6.(1+x)$), machine M_2 works in stationary regime at cycle time c_{2s}.
In the transitory working regime the cycle time (c_{2t}) is higher than the cycle time in the stationary regime (c_{2s}), which means that machine M_2 in transitory regime works physically at a cycle time, which corresponds to the cycle time of the stationary regime (c_{2s}) and it is waiting during a cycle time (c_{2t}-c_{2s}) for the next pair of transport and assembly pallets to be processed. Notice that, while $n_{4,2}$ and $n_{1,2}$ increase in the stationary working regime and approach the minimum contents ($n_{4,2\ min}$ and $n_{2,1\ min}$), the cycle time in transitory regime (c_{2t}) tends to approximate to the cycle time in stationary regime (c_{2s}) and the waiting cycle time tends to zero.

Figure 3. *Relationships between the cycle time of machine M_2 in transitory (c_{2t}) and stationary regimes (c_{2s}), the number of pallets existing in its upstream buffers ($n_{1,2}$ and $n_{4,2}$) and the values of x.*

Figure 4 represents the relationships between the cycle time in transitory (c_{3t}) and stationary (c_{3s}) regimes in the chassis assembly line (M_3), according to: Equations (13) and (16) for the transitory and stationary regimes and the values of Tables (3) and (4).

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The relationships between the cycle time of machine M_3 in transitory regime (c_{3t}) and the numbers of pallets ($n_{2,3}$ and $n_{7,3}$) existing in its upstream buffers $B_{2,3}$ and $B_{7,3}$ are shaped like exponential decay functions while $n_{2,3}<n_{2,3\ min}$ and $n_{7,3}<n_{7,3\ min}$, respectively, i.e. as the numbers of pallets ($n_{2,3}$ and $n_{7,3}$) existing in the upstream buffers $B_{2,3}$ and $B_{7,3}$ increase, the cycle time in transitory regime (c_{3t}) decreases, if machine M_3 does not remain blocked by its downstream buffers $B_{3,4}$ and $B_{3,7}$, according to the blocking conditions expressed in Table 1.

As a consequence of buffers $B_{2,3}$ and $B_{7,3}$ contain car body and front axle transport and assembly pallets, respectively, and their downstream machine (M_3) process car body transport and assembly pallets, which are univocally related to each other, their minimum contents ($n_{2,3\ min}$ and $n_{7,3\ min}$) required for the stationary working regime of their downstream machine (M_3) do not depend on the fourdoor cars ratio (x).

Notice that machine M_3 is governed by the upstream buffer, which feeds it at a lower frequency depending on the existing number of pallets. In accordance with this aspect, if the numbers of pallets existing in both upstream buffers do not reach their minimum values ($n_{2,3}<n_{2,3\ min}$ and $n_{7,3}<n_{7,3\ min}$) the cycle time of the downstream machine M_3 is governed by buffer which contributes to a higher value at transitory regime.

If the number of pallets in one of the upstream buffers is at least equal to its minimum value ($n_{j,3}\geq n_{j,3\ min}$) and the number of pallets in the other one does not reach its minimum value ($n_{k,3}<n_{k,3\ min}$) the cycle time of the downstream machine M_3 is governed by buffer $B_{k,3}$, which corresponds a higher cycle time.

When the numbers of pallets existing in the buffers $B_{2,3}$ and $B_{7,3}$ reach their minimum values ($n_{2,3\ min}=12$ and $n_{7,3\ min}=10$), according to Table (4), the downstream machine M_3 works in stationary regime at cycle time c_{3s}, which remain constant while the numbers of pallets existing in the buffers $B_{2,3}$ and $B_{7,3}$ increase ($n_{2,3}\geq n_{2,3\ min}$ and $n_{7,3}\geq n_{7,3\ min}$).

As described in Figures (2) and (3), the cycle time of machine M_3 (c_{3t}) is higher than the cycle time in the stationary regime (c_{3s}), which means that machine M_3 in transitory regime works physically at a cycle time, which corresponds to the cycle time of the stationary regime (c_{3s}) and it is waiting during a cycle time (c_{3t}-c_{3s}) for the next pair of transport and assembly pallets to be processed. Notice that, while $n_{4,2}$ and $n_{1,2}$ increase in the stationary working regime and approach the minimum contents ($n_{2,3\ min}$ and $n_{7,3\ min}$), the cycle time in transitory regime (c_{3t}) tends to approximate to the cycle time in stationary regime (c_{3s}) and the waiting cycle time tends to zero.

Figure 4. *Relationship between the cycle time of machine M_3 in transitory (c_{3t}) and stationary regimes (c_{3s}) and the number of pallets existing in its upstream buffers ($n_{2,3}$ and $n_{7,3}$)*

Figure 5 represents the relationships between the cycle time in the second branch (M_4) of the main automobile assembly line in transitory (c_{4t}) and stationary (c_{4s}) regimes, the numbers of pallets existing in its upstream buffers ($B_{3,4}$ and $B_{6,4}$) and the fourdoor cars ratio (x), according to: Equations (14) and (17) for the transitory and stationary working regimes and the values of Tables (3) and (4).

These relationships continue being valid if machine M_4 is not blocked by one of its downstream buffers ($B_{4,1}$ and $B_{4,2}$) according to the blocking conditions expressed in Table 1.

According to Equation (14), the relationship between the cycle time of machine M_4 in transitory regime (c_{4t}) and the numbers of pallets ($n_{3,4}$) is shaped like a exponential decay function, which does not depend on x, as is shown by the left curve of Figure (5). However, the relationship between the cycle time of machine M_4 in transitory regime (c_{4t}) and the numbers of pallets ($n_{6,4}$) is also shaped like a exponential decay function, which depends on x, as is shown by the right curve of Figure (5). In this case, notice, that $n_{6,4\ min}$ depends on x too.

Because machine M_4 is fed by two buffers ($B_{3,4}$ and $B_{6,4}$) its cycle time is governed by the upstream buffer, which feeds it at a lower frequency. According to this aspect, if the numbers of pallets existing in both upstream buffers do not reach their minimum values ($n_{3,4}<n_{3,4\ min}$ and $n_{6,4}<n_{6,4\ min}$) the cycle time of the downstream machine M_4 is governed by the buffer, which contributes to a higher value at transitory regime. Equally, if the number of pallets in one of the upstream buffers is at least equal to its minimum value ($n_{j,4}\geq n_{j,4\ min}$) and the number of pallets in the other one does not reach its minimum value ($n_{k,4}<n_{k,4}$

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$_{min}$), the cycle time of the downstream machine M_4 is governed by buffer $B_{k,4}$, which corresponds a higher cycle time. When the numbers of pallets in both upstream buffers reach their minimum values ($n_{3,4}\geq 10$ and $n_{6,4}\geq 11.1.(1+x)$), according to Table (4), machine M_4 works in stationary regime at cycle time c_{4s}.
As described in Figures (2) to (4) the cycle time in transitory working regime (c_{4t}) is higher than the cycle time in the stationary regime (c_{4s}), which means that machine M_4 in transitory regime works physically at a cycle time, which corresponds to the cycle time of the stationary regime (c_{4s}) and it is waiting during a cycle time (c_{4t}-c_{4s}) for the next pair of transport and assembly pallets to be processed. It is important to state that, while $n_{3,4}$ and $n_{6,4}$ increase in the stationary working regime and approach the minimum contents ($n_{3,4\ min}$ and $n_{6,4\ min}$), the cycle time in transitory regime (c_{4t}) tends to approximate to the cycle time in stationary regime (c_{4s}) and the waiting cycle time tends to zero.
Notice that Figures (3) and (5) are similar since machines M_2 and M_4 are fed by two buffers, whose assembly pallets are not univocally related to each other.

Figure 5. *Relationships between the cycle time of machine M_4 in transitory (c_{4t}) and stationary regimes (c_{4s}), the number of pallets existing in its upstream buffers ($n_{3\ 4}$ and $n_{6,4}$) and the values of x*

Figure 6 represents the relationship between the cycle time in transitory (c_{5t}) and stationary (c_{5s}) regimes in the doors preassembly line (M_5), and the number of pallets existing in its upstream buffer ($B_{2,5}$) according to: Equations (10) and (11) for the transitory and stationary working regimes and the values of Tables (3) and (4).
The relationship between the cycle time of machine M_5 in transitory regime (c_{5t}) and the number of pallets ($n_{2,5}$) existing in its upstream buffer ($B_{2,5}$) is shaped like an exponential decay function while $n_{2,5}<n_{2,5\ min}$, i.e. as the number of pallets $n_{2,5}$ increase, the cycle times in transitory regime (c_{5t}) decrease, if machine M_5 does not remain blocked by its downstream buffer $B_{5,6}$.
In the transitory working regime the cycle time (c_{5t}) is higher than the cycle time in the stationary regime (c_{5s}), which means that machine M_5 in transitory regime works physically at a cycle time, which corresponds to the cycle time of the stationary regime (c_{5s}) and it is waiting during a cycle time (c_{5t}-c_{5s}) for the next transport and assembly pallet to be processed. Notice that, while $n_{2,5}$ increases in the stationary working regime and approaches to the minimum contents ($n_{2,5\ min}$), the cycle time in transitory regime (c_{5t}) tends to approximate to the cycle time in stationary regime (c_{5s}) and the waiting cycle time tends to zero.
As has been discussed in Figures (2) to (5), when the number of pallets in buffer $B_{2,5}$, reaches its minimum value ($n_{2,5\ min}$=40), according to Table (4), the downstream machine M_5 begins to work in stationary regime at cycle time c_{5s}, which remains constant while the numbers of pallets increase ($n_{2,5}\geq n_{2,5\ min}$).

Figure 6. *Relationships between the cycle time of machine M_5 in transitory (c_{5t}) and stationary regimes (c_{5s}) and the number of pallets existing in its upstream buffer ($n_{2,5}$)*

Figure 7 represents the relationship between the cycle time in transitory (c_{6t}) and stationary (c_{6s}) regimes in the doors inspection line (M_6), and the number of pallets existing in its upstream buffer ($B_{5,6}$) according to: Equations (10) and (11) for the transitory and stationary working regimes and the values of Tables (3) and (4).
The relationship between the cycle time of machine M_6 in transitory regime (c_{6t}) and the number of pallets ($n_{5,6}$) existing in its upstream buffer ($B_{5,6}$) is shaped like a exponential decay function while $n_{5,6}<n_{5,6\ min}$, i.e. as the number of pallets $n_{5,6}$ increase, the cycle times in transitory regime (c_{6t}) decrease, if machine M_5 does not remain blocked by its downstream buffer $B_{6,4}$.
In the transitory working regime the cycle time (c_{6t}) is higher than the cycle time in the stationary regime (c_{6s}), which means that machine M_6 in transitory regime works physically at a cycle time, which corresponds to the cycle time of the stationary regime (c_{6s}) and it is waiting during a cycle time (c_{6t}-c_{6s}) for the next transport and assembly pallet to be processed. Notice that, while $n_{5,6}$ increases in the stationary

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working regime and approaches to the minimum contents ($n_{5,6\ min}$), the cycle time in transitory regime (c_{6t}) tends to approximate to the cycle time in stationary regime (c_{6s}) and the waiting cycle time tends to zero.
As has been discussed in Figures (2) to (6), when the number of pallets in the buffer $B_{5,6}$, reach its minimum value ($n_{5,6\ min}$=5), according to Table (4), the downstream machine M_6 begins to work in stationary regime at cycle time c_{6s}, which remain constant while the numbers of pallets increase ($n_{5,6} \geq n_{5,6\ min}$).

Figure 7. *Relationships between the cycle time of machine M_6 in transitory (c_{6t}) and stationary regimes (c_{6s}) and the number of pallets existing in its upstream buffer ($n_{5,6}$)*

Figure 8 represents the relationship between the cycle time in transitory (c_{7t}) and stationary (c_{7s}) regimes in the front axle preassembly line (M_7), and the number of pallets existing in its upstream buffer ($B_{3,7}$) according to: Equations (10) and (11) for the transitory and stationary working regimes and the values of Tables (3) and (4).
The relationship between the cycle time of machine M_7 in transitory regime (c_{7t}) and the number of pallets ($n_{3,7}$) existing in its upstream buffer ($B_{3,7}$) is shaped like a decay exponential function while $n_{3,7} < n_{3,7\ min}$, i.e. as the number of pallets $n_{3,7}$ increase, the cycle times in transitory regime (c_{7t}) decrease, if machine M_7 does not remain blocked by its downstream buffer $B_{7,3}$.
In the transitory working regime the cycle time (c_{7t}) is higher than the cycle time in the stationary regime (c_{7s}), which means that machine M_7 in transitory regime works physically at a cycle time, which corresponds to the cycle time of the stationary regime (c_{7s}) and it is waiting during a cycle time (c_{7t}-c_{7s}) for the next transport and assembly pallet to be processed. Notice that, while $n_{3,7}$ increases in the stationary working regime and approaches to the minimum contents ($n_{3,7\ min}$), the cycle time in transitory regime (c_{7t}) tends to approximate to the cycle time in stationary regime (c_{7s}) and the waiting cycle time tends to zero.
As has been discussed in Figures (2) to (7), when the number of pallets, that exists in the buffer $B_{3,7}$, reach its minimum value ($n_{3,7\ min}$=10), according to Table (4), the downstream machine M_7 begins to work in stationary regime at cycle time c_{6s}, which remain constant while the numbers of pallets increase ($n_{3,7} \geq n_{3,7\ min}$).

Figure 8. *Relationships between the cycle time of machine M_7 in transitory (c_{7t}) and stationary regimes (c_{7s}) and the number of pallets existing in its upstream buffer ($n_{3,7}$)*

Since machines M_1, M_5, M_6 and M_7 are fed by only one buffer, Figures (2), (6), (7) and (8) are similar to each other except for: the minimal contents of their upstream buffers according to Table (4), their cycle times in stationary regime, according to Table (2), and the form of decay exponential functions according to Equation (10).
In the same manner, Figures (3) and (5) are formed by three dimensional decay exponential functions similar to each other since both machines are fed by two buffers, which contain transport and assembly pallets not univocally related to each other, i.e. related via the additional variable x.

5. Conclusions

In this work an existing automobile assembly line and the correspondent preassembly lines have been analyzed as a network of four closed loops of machines and intermediate buffers, formed by linear conveyors along which the transport and assembly pallets move from one line to the other at a steady speed.
In spite of the significance of this kind of assembly lines, the networks of closed loops of machines and intermediate buffers, formed by conveyors, have not yet been investigated. With this study a better knowledge of this kind of manufacturing system is attained.

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As intermediate buffers are formed by conveyors, transport and assembly pallets require time to arrive to the downstream machine once they have been processed by the upstream machine. Hence, the machines of the closed loops work at cycle times, which depend on the number of pallets existing in their upstream buffers. Thus, the cycle times of machines fed by several buffers are governed by the upstream buffer, which feeds them at a lower frequency.

This work has analyzed the relationship between the cycle times of the machines and the number of pallets in their upstream buffers, defining the transitory and stationary working regimes. The main conclusions that can be extracted from this analysis are that cycle times in transitory regime depend on the number of pallets in their upstream buffers according to exponential decay functions, while cycle times remain constant in the stationary working regime. The assembly line usually works in stationary state. In case of disruption of any machine of the closed loops its downstream machines work in transitory regime. The importance of the transient analysis is the optimization of the entire system after disruption of one machine in order to maximize the units produced by the main assembly line.

In spite of the fact that literature considers that machines process pallets, which are univocally related to each other, some of the different preassembly lines analyzed process pallets, which are not univocally related with the car body transport and assembly pallets. Thus, the cycle times in transitory regime of machines, fed by several buffers, depend on the number of pallets in their upstream buffers and their relationship, governed by an external variable.

The cycle times of most real assembly and preassembly lines decoupled by intermediate buffers, under normal working conditions, are related to each other in order to guarantee the production rate of the complete system. However, these relationships have not been tackled by existing literature. Due to these relationships, the cycle times of the different preassembly lines in stationary regime can be calculated according to the production rate of the assembly line required.

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Table 1. Blocking and starvation conditions of each machine

Machine	Blocking	Starvation
M_1	If $n_{1,2}=n_{1,2\ max.}$ and $\eta_1>\eta_2$	If $n_{4,1}=0$
M_2	If $n_{2,5}=n_{2,5\ max.}$ and $\eta_2.(1+x)>\eta_5$ or $n_{2,3}=n_{2,3\ max.}$ and $\eta_2>\eta_3$	If $n_{1,2}=0$ or $n_{4,2}=0$
M_3	If $n_{3,4}=n_{3,4\ max.}$ and $\eta_3>\eta_4$ or $n_{3,7}=n_{3,7\ max.}$ and $\eta_3>\eta_7$	If $n_{2,3}=0$ or $n_{7,3}=0$
M_4	If $n_{4,1}=n_{4,1\ max.}$ and $\eta_4>\eta_1$ or $n_{4,2}=n_{4,2\ max.}$ and $\eta_4>\eta_2$	If $n_{6,4}=0$ or $n_{3,4}=0$
M_5	If $n_{5,6}=n_{5,6\ max.}$ and $\eta_5>\eta_6$	If $n_{2,5}=0$
M_6	If $n_{6,4}=n_{6,4\ max.}$ and $\eta_6>\eta_4.(1+x)$	If $n_{5,6}=0$
M_7	If $n_{7,3}=n_{7,3\ max.}$ and $\eta_7>\eta_3$	If $n_{3,7}=0$

Table 2. Cycle times in stationary regime of machines M_1 to M_7

Machine	Cycle time in stationary regime
M_1	c_{1s} = 1.07 min./pallet
M_2	c_{2s} = 1.07 min./pallet
M_3	c_{3s} = 0.92 min./pallet
M_4	c_{4s} = 1.08 min./pallet
M_5	c_{5s} = 0.62 min./pallet
M_6	c_{6s} = 0.62 min./pallet
M_7	c_{7s} = 1.06 min./pallet

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Table 3. Lengths of conveyors ($l_{i,j}$), average storing length ($l_{aspi,j}$) per pallet and transportation speed ($v_{i,j}$) of assembly pallets in each intermediate buffer ($B_{i,j}$)

Buffer	$l_{i,j}$	$l_{aspi,j}$	$v_{i,j}$
$B_{1,2}$	$l_{1,2}$ = 357 m	$l_{asp1,2}$ = 4.46 m/pallet	$v_{1,2}$ = 16 m/min.
$B_{2,3}$	$l_{2,3}$ = 174 m	$l_{asp2,3}$ = 4.70 m/pallet	$v_{2,3}$ = 16 m/min.
$B_{3,4}$	$l_{3,4}$ = 165 m	$l_{asp3,4}$ = 5.50 m/pallet	$v_{3,4}$ = 16 m/min.
$B_{4,1}$	$l_{4,1}$ = 533 m	$l_{asp4,1}$ = 4.33 m/pallet	$v_{4,1}$ = 16 m/min.
$B_{2,5}$	$l_{2,5}$ = 618 m	$l_{asp2,5}$ = 1.87 m/pallet	$v_{2,5}$ = 25 m/min.
$B_{5,6}$	$l_{5,6}$ = 74 m	$l_{asp5,6}$ = 1.89 m/pallet	$v_{5,6}$ = 25 m/min.
$B_{6,4}$	$l_{6,4}$ = 300 m	$l_{asp6,4}$ = 1.86 m/pallet	$v_{6,4}$ = 25 m/min.
$B_{4,2}$	$l_{4,2}$ = 230 m	$l_{asp4,2}$ = 1.85 m/pallet	$v_{4,2}$ = 25 m/min.
$B_{3,7}$	$l_{3,7}$ = 434 m	$l_{asp3,7}$ = 2.76 m/pallet	$v_{3,7}$ = 45 m/min.
$B_{7,3}$	$l_{7,3}$ = 374 m	$l_{asp7,3}$ = 2.77 m/pallet	$v_{7,3}$ = 45 m/min.

Table 4. Minimum contents ($n_{i,j\ min}$) for the stationary working regime and maximum capacities ($n_{i,j\ max}$) in both working regimes of each intermediate buffer ($B_{i,j}$)

Buffer	$n_{i,j\ min}$	$n_{i,j\ max}$
$B_{1,2}$	$n_{1,2\ min}$ = 21 pallets	$n_{1,2\ max}$ = 80 pallets
$B_{2,3}$	$n_{2,3\ min}$ = 12 pallets	$n_{2,3\ max}$ = 37 pallets
$B_{3,4}$	$n_{3,4\ min}$ = 10 pallets	$n_{3,4\ max}$ = 30 pallets
$B_{4,1}$	$n_{4,1\ min}$ = 31 pallets	$n_{4,1\ max}$ = 123 pallets
$B_{2,5}$	$n_{2,5\ min}$ = 40 pallets	$n_{2,5\ max}$ = 330 pallets
$B_{5,6}$	$n_{5,6\ min}$ = 5 pallets	$n_{5,6\ max}$ = 39 pallets
$B_{6,4}$	$n_{6,4\ min}$ = 11.1.(1+x) pallets	$n_{6,4\ max}$ = 161 pallets
$B_{4,2}$	$n_{4,2\ min}$ = 8.6.(1+x) pallets	$n_{4,2\ max}$ = 124 pallets
$B_{3,7}$	$n_{3,7\ min}$ = 10 pallets	$n_{3,7\ max}$ = 157 pallets
$B_{7,3}$	$n_{7,3\ min}$ = 10 pallets	$n_{7,3\ max}$ = 135 pallets

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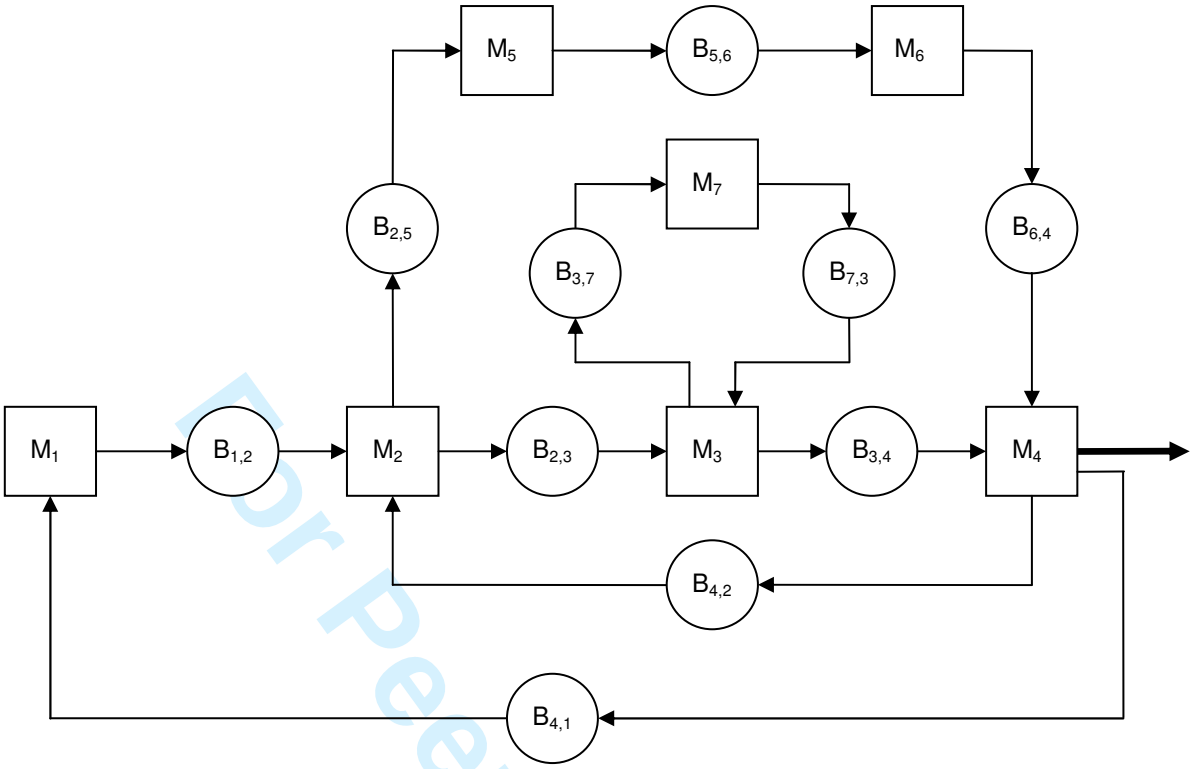

Figure 1

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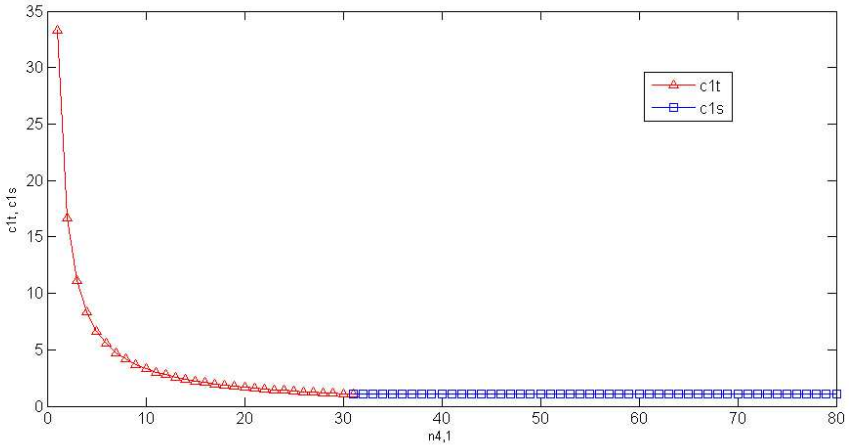

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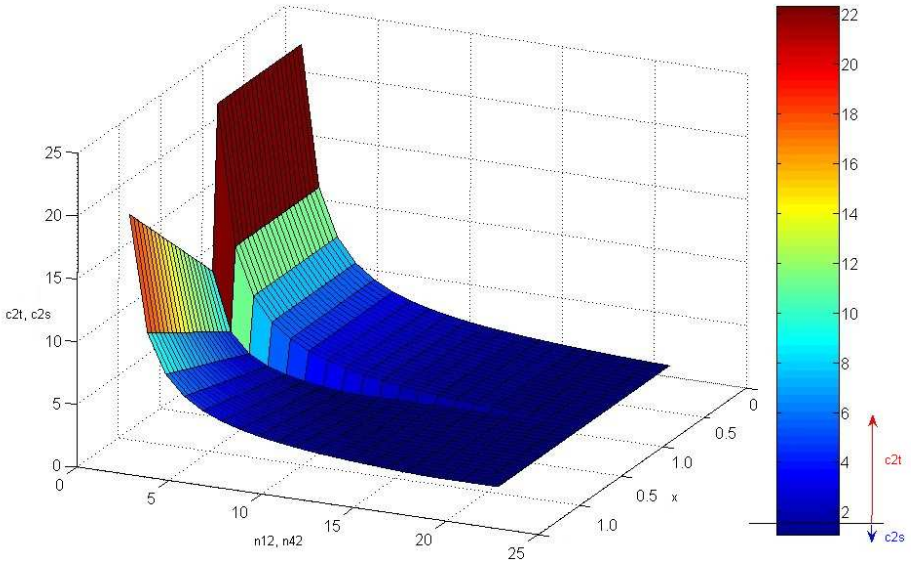

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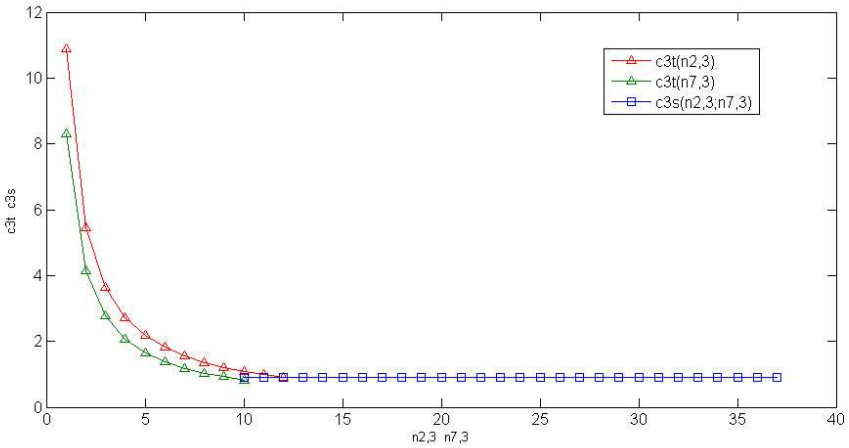

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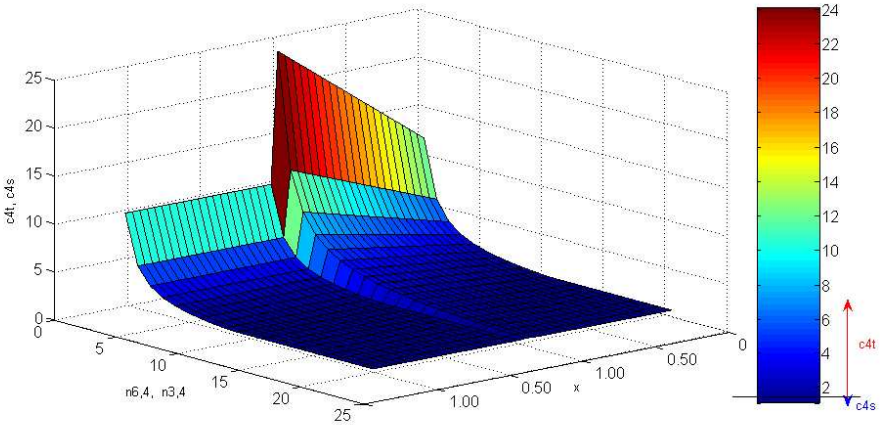

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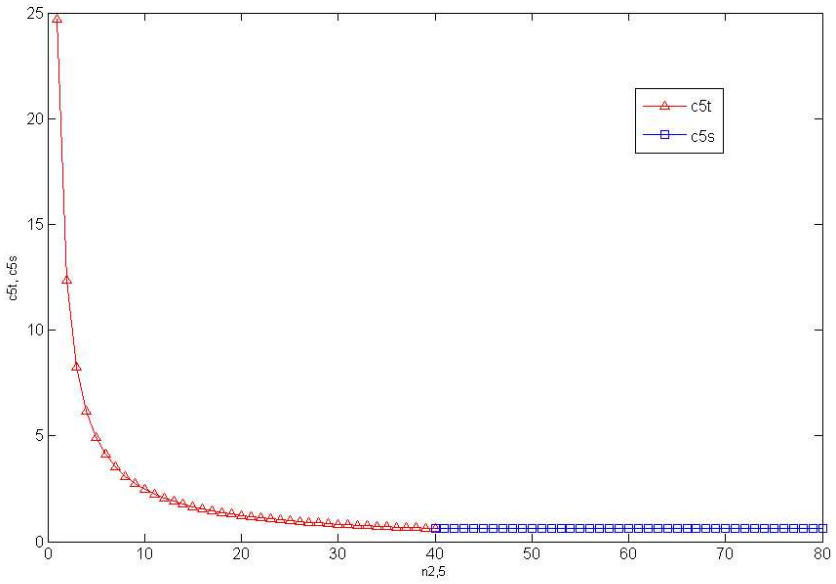

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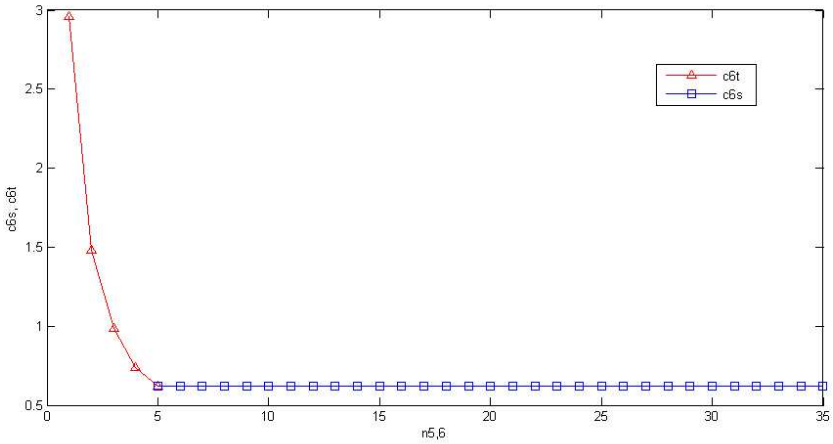

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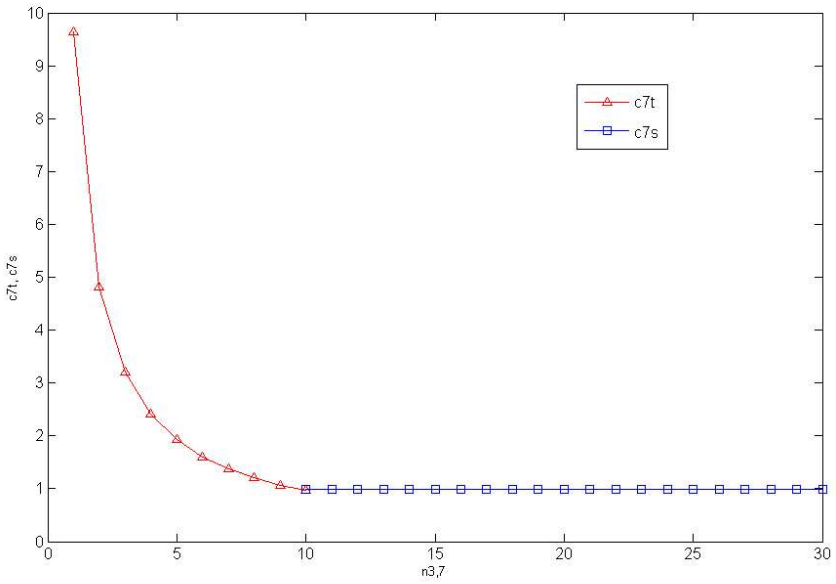

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