OPTIMIZING SUPPLY CHAIN NETWORK DESIGN WITH SALBP-E ASSEMBLY LINE ISSUE

[1*]Raji, Ibrahim. O. and [2]Rossi, Tommaso
Center for Supply Chain, Operations & Logistics Management
LIUC - Università Carlo Cattaneo
Castellanza 21053 (VA) Italy
[1]iraji@liuc.it; [2]trossi@liuc.it

Abstract

Optimizing Supply Chain Network (SCN) system, otherwise known as “strategic decision”, with assembly line balancing issue (tactical decision) is relatively at infant level in literature. Managers and decision makers usually will not disregard either of these activities (either disregard SCN activities while trying to balance assembly lines or assembly line balancing while designing an SCN) for an SCN system that has assembly line unit. These two key subjects are collaborative.

This work focuses on advancing optimization criteria from one of the pioneering work in this research field by designing a mathematical model to optimize the SCN that includes the manufacturers/producers, assemblers and end users. The goal is to simultaneously minimize the transportation costs along the SCN line for the concerned time phases while balancing the assembly lines in assemblers so as to minimize the overall cost of setting up stations. A mixed-integer nonlinear model is proposed to minimize the transportation costs alongside the cycle time and number of stations at the assembler. This means minimizing the idle time and also maximizing the line efficiency by increasing the throughput rate in addition to the cost minimization. We propose to apply the model to real life data and subsequently recommend its deployment.

Keywords: Assembly Line Balancing; SALBP-E; Supply Chain Network system; Mixed-Integer Nonlinear Programming.

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[*] Corresponding author.

1.0. Introduction

Supply Chain Network (SCN) system problem is one of the problems that have received much attention in a couple of years now. Beamon (1998) and Mula et al. (2010), as well as several others, provide insight reviews on this topic. The sole aim of SCN system design is to ensure coordination among various components that make up the SCN through parts and component supply, the production and manufacturing as well as the distribution of the concerned fished goods in a way that benefits the entire SCN members viz-a-viz the Suppliers, Producers / Manufacturers and the end customers.

The design of SCN system operates at three basic levels which are identified by Paksoy *et al.*, (2012); Paksoy and Özceylan, (2012) as "strategic, tactical and operational levels". "The strategic approach is concerned with the network resource optimization which includes networks designing, positioning and determination of the required number of facilities, etc., whereas tactical decisions involve the mid-term, including plants' production levels, inventory levels and optimal lot quantities, assembly policy. Operational decisions focus on the realization of the tactical decisions in the shortest term possible, for instance, scheduling, production planning and control" (Paksoy *et al.,* 2012).

Strategic decisions pose a lasting result on the SCN structure. Consequently, tactical decisions are sturdily reliant on strategic decisions; hence, several benefits exist in the simultaneous study of the two decision types (Pereira and Vila, 2015). This work mainly examines how the optimization of strategic and tactical decisions in the SCN system can be realized concomitantly.

According to Pereira and Vila (2015), the relevance of studying assembly line balancing has been methodically emphasized by Cachon and Terwiesch (2013) as a way of improving productivity as well as reduction of the associated costs of operation. Thus, it is suitable to consider line balancing within SCN design so as to align likely savings within the SCN. This was pointed out by Paksoy *et al.* (2012) in their pioneer work on simultaneous optimization of strategic and tactical decisions in the SCN system. Few other researches have followed this pioneering work and details would be presented in the next section.

Assembly line is regarded as a form of production system consisting of transportation devices to convey unfinished goods, usually called work in progress (WIP) along a number of workstations, where the process of assembly is accomplished. The assembly activity usually involves elemental tasks requiring a specific element of time/duration for accomplishment. The tasks usually have precedence relationships that define what task needs to be accomplished before the commencement of another, for example, automobile assembly requires installation of the rim before the wheels. The assembly line balancing problem (ALBP) basically involves the determination of the optimal allocation of tasks and/or resources to the various workstations while achieving the target objectives.

According to Pereira and Vila (2015), "several balancing problems can be generated by considering different technical characteristics of the line, or by considering different objectives" (Scholl and Becker, 2006; Battaia and Dolgui, 2013). "However, a significant part of the literature regarding ALBPs is devoted to the basic formulation upon which the rest of the ALBPs are built. This basic formulation is regarded as the simple assembly line balancing problem (SALBP)" (Wei and Chao, 2011; Pereira and Vila 2015).

Various versions of the SALPB have been reported in literature ranging from SALBP-1 which attempts to minimize the number of stations given the cycle time; SALBP-2 that minimizes the cycle time for a given number of stations as well as SALBP-E that combines the SALBP-1 and SALBP-2 and maximizes the line efficiency or equivalently line capacity by simultaneously minimizing both number of stations and cycle time (Yolmeh and Salehi, 2015). However, production and assembly line managers argue that "minimisation of the number of workstations and minimisation of the cycle time are the most significant goals of assembly line balancing" (Paksoy *et al.*, 2012). Hence, the goal that combines the 2, i.e. SALBP-E is considered in the assembly line part of this research which is geared towards minimizing the idle time and maximizing the line efficiency.

This work develops a mixed integer nonlinear mathematical model which is an extension of the model by Paksoy et al. (2012). While they considered a SALBP-1 with the supply chain design problem, this study considers SALBP-E type which combines both SALBP-1 and SALBP-2 that minimizes the idle time and maximizes the line efficiency via simultaneous minimization of both number of stations and cycle time (Wei and Chao, 2011; Yolmeh and Salehi, 2015). Also, choice of SALBP-E is to ensure the continuous return of feasible assignment of tasks that maximize line efficiency as the SCN design parameters continue to change. A change in SCN parameters, such as demand and production level, automatically changes the cycle time or required number of stations. Hence, SALBP-E will better ensure maximization of the line efficiency by increasing the throughput rate of the line.

The mathematical model is able to support the SC node capacity decision so as to increase the effectiveness of the SCN as well as the line efficiency (thanks to the incorporation of an upper limit for the cycle time and the minimization of the number of stations in the assembler). It is thus used to optimize the SCN, consisting of manufacturers, assemblers and customers, with the goal of minimizing the costs of transportation for the concerned periods/time phases while balancing the assembly lines in assemblers so as to minimize the aggregate cost of setting up stations concomitantly; hence, translating to improvement of the line efficiency.

2.0. Review of Literature

Supply chain management has gotten significant interest among researchers, academicians and practitioners in some time past with the designing and optimization of SCNs being the most explored areas in the field (Paksoy et al., 2012; Paksoy and Özceylan, 2012). At that, several arithmetical/exact and heuristic/empirical models have been suggested. Most of these models are usually connected with the distribution/transportation networks with some added thoughts such as facility location to be started (plants, distribution centres); network configuration design; customer demand satisfaction with overall cost minimization, transportation cost, purchase cost among several others (Paksoy and Chang 2010; Paksoy et al., 2012).

However, studies focusing on simultaneous modelling of SCN design with assembly line balancing problems are still at its infant stage in the literature and thus; received very little consideration among the researchers in this interesting field.

Elucidating the importance of assembly line balancing in SCN design problems, Che et al. (2009) stated that “the operation mechanism of a supply chain is comparable to an assembly line production system”. Thus, “they attempt adopting line balancing technology to complete co-operator selection and industry assignment for the cooperation mechanism with the lower delivery delay loss of the supply chain network” (Pereira and Vila, 2015). Albeit, assembly line balancing was applied to the SCN problem they considered, simultaneous consideration was not considered. According to Paksoy et al., 2012, Che and Chiang (2010) “focused on carrying out supply chain planning for a build-to-order supply chain network. The planning was designed to integrate supplier selection and product assembly with the logistic distribution system of the supply chain in order to meet the market demand. Three evaluation criteria were considered which are costs, delivery time, and quality. A multi-objective optimisation mathematical model was subsequently established for build-to-order supply chain planning. However, line balancing was not considered” (Paksoy et al., 2012).

Paksoy et al. (2012) are the first to incorporate SCN designing problem with assembly line balancing. There are three entities in this pioneering work namely - “manufacturers, assemblers and customers”. The manufacturers produce the components and ship same to assemblers as required inputs for the assembly of the final products. The assemblers in return assemble the final product in answering the predictable demand of customers before subsequent shipment. Furthermore, manufacturers’ locations, as well as those of assemblers and end customers are taken to be fixed. The problem involves determination of the amount of components sent to the assemblers by the manufacturers as well as the shipment of assembled/end products from assemblers to the customers while simultaneously balancing the assembly lines in all assemblers based on the assigned demand. The problem was formulated as a “mixed integer non-linear programming (MINLP)” with the objective of minimizing the overall costs considering the costs of transportation alongside the fixed costs of the assembly line. The applicability of the model was demonstrated using a hypothetical numerical example.

Sequel to the pioneering work of Paksoy et al. (2012), few other researchers have followed with each building on the seminary work of Paksoy et al. (2012). Among this was that of Paksoy & Ozceylan (2012) where a U-shaped assembly line was assumed for the assemblers in place of the straight line model suggested by Paksoy et al. (2012). This study also proposed a “non-linear mixed-integer formulation for the SCN design problem incorporating U-shaped assembly line balancing decisions" (Paksoy & Ozceylan, 2012). Similar numerical example as the seminary work of Paksoy et al., (2012) was used to show the utility of the proposed model. The paper concluded and showed how advantageous it is to study the SCN design and the U-shaped ALBP simultaneously.

Also, Hamta et al. (2015) considered the design of SCN alongside assembly line balancing decisions in uncertain demand scenarios. "A two-stage mixed-integer stochastic programming formulation was proposed for the resolution of the SCN design and ALBP with demand uncertainty. Several sampling strategy methods were used to obtain solutions for the largest instances more efficiently while also testing the quality of the solutions of the sampling strategies as well as the formulation via the use of randomly generated instances" (Pereira and Vila, 2015).

Still tolling the demand uncertainty lane, Yolmeh and Salehi (2015) also developed a "two-stage stochastic programming" formulation for the "exact resolution of the problem of demand uncertainty". A method tagged "outer approximation (OA)" was proposed to find good solutions to large problems in reduced times, which ordinarily will require large polynomial computation times. The OA method was found to obtain good results effectively and efficiently.

Still corroborating on the seminary work of Paksoy et al., (2012), Pereira and Vila (2015) proposed some alternative formulation to that of Paksoy et al., (2012) by decomposing the problem into a sequence of SALBP-2 (having pointed out that SALBP-1 methods can be employed for SALBP-2) and a mixed-integer linear programming model. "The mixed-integer linear program considers the transportation costs and represents the line balancing costs using a piecewise function obtained by the sequence of line balancing problems". The study reported that the decomposition was capable of solving the example used by Paksoy et al., (2012) in lesser computational times.

All the above works no doubt have a similar thing in common, which is to advance on the pioneering work of Paksoy et al., (2012) with diverse modification viewpoints.

This work also attempts to go step further by developing a mixed integer nonlinear mathematical model that supports the SC node capacity decision so as to increase the effectiveness of the SCN as well as the line efficiency (thanks to the incorporation of an upper limit for the cycle time and the minimization of the number of stations in the assembler). The model is to optimize the SCN, consisting of manufacturers, assemblers and customers. The overall goal is to minimize the transportation costs for the concerned periods while balancing the assembly lines in assemblers in order to minimize the total cost of setting up stations concomitantly. While Paksoy et al., (2012) considered a SALBP-1 with the SCN design problem, this study considers SALBP-E type (which combines both SALBP-1 and SALBP-2) that simultaneously maximizes the line efficiency and minimizes the idle time via concomitant minimization of both number of stations and cycle time (Wei and Chao, 2011; Yolmeh and Salehi, 2015). As stated earlier, choice of SALBP-E is to ensure the continuous return of feasible assignment of tasks that maximize line efficiency as the SCN design parameters continue to change. A change in SCN parameters, such as demand and production level, automatically changes the cycle time or required number of stations. Hence, SALBP-E will better ensure maximization of the line efficiency together with minimization of idle time. The mathematical model is used to optimize the SCN with the goal of minimizing the transportation costs for the concerned periods while balancing the assembly lines in assemblers in order to minimize the total cost of setting up stations concomitantly thereby translating to the improvement of the line efficiency at reduced idle time.

3.0. Problem formulation

As stated earlier, this work focuses on advancing the work of Paksoy et al., (2012). Their original mathematical problem formulation is first introduced after which the points that form the motive of advancement in the formulation are highlighted and subsequently reformulation is proposed. Sub-section 3.1 presents the original problem formulation while 3.2 propose the modified model.

3.1. A mathematical formulation for the joint SCN design and assembly line balancing problem

The mathematical model from Paksoy et al., (2012) is first presented to allow for comprehension of the problem under study. The following parameters are used in the model:

M: “collection of Manufacturers ($m \epsilon M$)”;

A: “collection of Assemblers ($a \epsilon A$)”;

C: “collection of customers ($c \epsilon C$)”;

P: “collection of periods ($p \epsilon P$)”;

K: “collection of components ($k \epsilon K$)”.

J: “number of stations (upper bound) which can be estimated from a heuristic procedure”;

N: “collection of tasks ($i; r; s \epsilon N$)”;

L: “collection of precedence relations where ($r; s$) ϵ L means a precedence relation between tasks r and s (r is an immediate predecessor of s)”;

t_i: “processing time of task i (time units)”;

W_p: “working time in period p (time units)”;

a_{mkp}: “capacity of manufacturer m for component k in period p (units)”;

b_{ap}: “capacity of assembler a in period p (units)”;

u_{cp}: “demand of customer c in period p (units)”;

C_{map}: “unit cost of shipping from manufacturer m to assembler a in period p (monetary units /distance units per unit)”;

C_{acp}: “unit cost of shipping from assembler a to customer c in period p (monetary units/distance units per unit)”.

D_{ma}: “distance between manufacturer m and assembler a (distance units)”;

D_{ac}: “distance between assembler a and customer c (distance units)”;

O: “fixed cost of opening a station in the assembly line in all periods (monetary units)” (Paksoy et al., 2012).

The variables adopted in the model are as follows:

X_{makp}: “units shipped from manufacturer m to assembler a for component k in period p”;

Y_{acp}: “units shipped from assembler a to customer c in period p”;

V_{aijp}: “binary variable that takes value 1 if assembler a performs task i in workstation j in period p, and 0 otherwise”;

Z_{ajp}: “binary variable that takes value 1 if there is any task assigned to workstation j for assembler a in period p”;

CT_{ap}: “cycle time for assembler a in period p” (Paksoy et al., 2012).

Using the foregoing notations, the SCN design problem with incorporated assembly line balancing is thus presented as follows:

Objective function:

$$\text{Min } Z_1 + Z_2 \qquad (1)$$

Where;

$$Z_1 = \sum_m^M \sum_a^A \sum_k^K \sum_p^P C_{map} \ D_{ma} X_{makp} + \sum_a^A \sum_c^C \sum_p^P C_{map} \ D_{ac} Y_{acp} \qquad (2)$$

$$Z_2 = \sum_a^A \sum_j^J \sum_p^P Z_{ajp} \,.\mathrm{O} \qquad (3)$$

The objective function has Z_1 that minimizes the total shipping costs of the 2 stages (Manufacturer – Assembler and Assembler – Customer) in the SCN at any period; Also Z_2 that represent the fixed costs of operating assembly stations at any period. Z_2 is, therefore, the term that finds the feasible assignment of tasks that minimizes the sum of fixed costs.

Constraints:

$$\sum_a^A X_{makp} \leq a_{mkp} \quad \forall\, m,k,p \qquad (4)$$

$$\sum_c^C Y_{acp} \leq b_{ap} \quad \forall\, a,p \qquad (5)$$

$$\sum_a^A Y_{acp} \geq U_{cp} \quad \forall\, c,p \qquad (6)$$

$$\sum_a^A X_{makp} = \sum_c^C Y_{acp} \quad \forall\, a,k,p \qquad (7)$$

$$\sum_j^J V_{aijp} = 1 \quad \forall\, a,i,p \qquad (8)$$

$$\sum_j^J V_{arjp} - \sum_j^J V_{asjp} \leq 0 \quad \forall\, a,r,s \in L; p \qquad (9)$$

$$\sum_j^J t_i \,.\, V_{aijp} \leq CT_{ap} \quad \forall\, a,j,p \qquad (10)$$

$$CT_{ap} = \frac{W_{time}}{\sum_c^C Y_{acp}} \quad \forall\, a,p \qquad (11)$$

$$\sum_i^N V_{aijp} - J\,.Z_{ajp} \leq 0 \quad \forall\, a,j,p \qquad (12)$$

$$X_{makp} \,;\, Y_{cp} \,;\, CT_{ap} \geq 0 \quad \forall m,a,k,c,p \qquad (13)$$

$$V_{aijp} \,;\, Z_{ajp} \in \{0,1\} \qquad (14)$$

"Constraints (4) and (5) ensure that the capacity of manufacturers and assemblers are not exceeded at any period during appropriate shipment respectively. Constraint (6) ensures customer's demand satisfaction at any period. Constraint (7) ensures that the total components transported from the manufacturers to the assembler must be equal to the shipped product quantity from the assembler to customers to guarantee customer's demand satisfaction at any period. Constraint (8) ensures that every task is assigned to only one station in all assemblers at any period. Constraint (9) is the precedence constraint that provides the precedence relationship by assigning task r as an immediate predecessor of task s in all assemblers at any period. Constraint (10) ensures that the cycle times are not exceeded for any station in all assemblers at any period. Constraint (11) implies that the cycle time is equal to the total working time in all periods divided by the total product quantity needed to be produced at all periods for the assemblers. As a matter of fact, constraint 11 is the linkage point of the SCN design problem and ALBP. Constraint (12) signifies that station j is used if any task is assigned to it in all assemblers at any period. Constraint (13) is the non-negativity limit on decision variables (X_{makp}, Y_{acp}, CT_{ap}). Constraint (14) is the non-divisibility constraint and states that any task can be assigned to a station as a whole or not" (Paksoy et al., 2012).

3.2. Proposed modified model

As stated, Paksoy et al., (2012) considered a SALPB-1 problem with the SCN design problem, in this section, we highlight the points that form the motive of advancement in the formulation.

1. Instead of the SALBP-1 that was considered in Paksoy et al., (2012), SALBP-E is proposed as it combines both SALBP-1 and SALBP-2; thus maximizing the line efficiency via simultaneous minimization of both number of station and cycle time (Wei and Chao, 2011 ; Yolmeh and Salehi, 2015). Also, choice of SALBP-E is to ensure the continuous return of feasible assignment of tasks that maximize line efficiency as the SCN design parameters continue to change. A change in SCN parameters, such as demand and production level, automatically changes the cycle time or required number of stations. Hence, SALBP-E will better ensure minimization of idle time and maximization of the line efficiency via increase of throughput rate. Using the logic of Wei and Chao (2011), the term Z_{ajp} in the SALBP-1 assembly line component Z_2 in Paksoy et al. (2012) is usually unknown and not easy to solve. In addition to this, the number of stations required by an assembler keeps increasing as SCN design parameter like production level increases for any given period; hence, additional binary variables are added to the Z_2 component. We introduce Z'_{ajp} as a variable that takes value 1 if j stations are opened in assembler a during period p, 0 therwise. In other words, attention is now shifted to the stations that are opened in assembler.
Hence, the objective function Z_2 is modified to Z'_2 as follows:

$$Z'_2 = \sum_a^A \sum_j^J \sum_p^P CT_{ap} \cdot jZ'_{ajp}\text{O} \qquad (15)$$

2. In line with modified Z_2 ; the maximum allowable cycle time CT_{max} is pre-set to enforce a maximum limit of cycle times (by increasing the throughput rate of the line) for any station at the assemblers. According to Wei and Chao, (2011), CT_{max} is preset as "the greater value between the maximum time of all tasks and the sum time of all tasks divided by 2" (Wei and Chao, 2011).

That is; $CT_{max} = \max[max\ t_i\ OR\ \frac{\sum t_i}{2}]$. (16)

Hence, the additional constraint to enforce a maximum limit of cycle times for any station at the assemblers is:

$$CT_{ap} \le CT_{max} \quad \forall a, p \qquad (17)$$

3. Also, precedence constraint defined by equation (9) does not comprise the multiplication by the corresponding station number. Hence, the precedence constraint defined by (9) is modified according to Wei and Chao, (2011) as follows:

$$\sum_j^J jV_{arjp} - \sum_j^J jV_{asjp} \le 0 \quad \forall\ a, r, s \in L; p \qquad (18)$$

Thus, the modified model consists of objective function (1) whose terms can be determined with cost functions in (2) and (15); the constraint sets (4) – (8), (18), (10) – (11), (17) as well as (12) – (14) respectively. The modified model is simply put in an orderly manner as follows:

Objective function:

$$\text{Min } Z_1 + Z'_2 \qquad (1^*)$$

Where;

$$Z_1 = \sum_m^M \sum_a^A \sum_k^K \sum_p^P C_{map}\ D_{ma} X_{makp} + \sum_a^A \sum_c^C \sum_p^P C_{map}\ D_{ac} Y_{acp} \qquad (2^*)$$

$$Z'_2 = \sum_a^A \sum_j^J \sum_p^P CT_{ap} \cdot jZ'_{ajp}\text{O} \qquad (3^*)$$

Constraints:

$$\sum_{a}^{A} X_{makp} \; \leq \; a_{mkp} \quad \forall\, m,k,p \tag{4*}$$

$$\sum_{c}^{C} Y_{acp} \; \leq \; b_{ap} \quad \forall\, a,p \tag{5*}$$

$$\sum_{a}^{A} Y_{acp} \; \geq \; U_{cp} \quad \forall\, c,p \tag{6*}$$

$$\sum_{a}^{A} X_{makp} = \sum_{c}^{C} Y_{acp} \quad \forall\, a,k,p \tag{7*}$$

$$\sum_{j}^{J} V_{aijp} = 1 \quad \forall\, a,i,p \tag{8*}$$

$$\sum_{j}^{J} jV_{arjp} - \sum_{j}^{J} jV_{asjp} \; \leq 0 \quad \forall\, a,r,s \in L; p \tag{9*}$$

$$\sum_{j}^{J} t_i \,.\, V_{aijp} \; \leq \; CT_{ap} \quad \forall\, a,j,p \tag{10*}$$

$$CT_{ap} = \frac{W_{time}}{\sum_{c}^{C} Y_{acp}} \quad \forall\, a,p \tag{11*}$$

$$CT_{ap} \; \leq \; CT_{max} \quad \forall a,p \tag{12*}$$

$$\sum_{i}^{N} V_{aijp} - J \,.\, Z_{ajp} \; \leq 0 \quad \forall\, a,j,p \tag{13*}$$

$$X_{makp} \,;\, Y_{cp} \,;\, CT_{ap} \; \geq 0 \quad \forall m,a,k,c,p \tag{14*}$$

$$V_{aijp} \,;\, Z_{ajp} \; \in \{0,1\} \tag{15*}$$

4.0. Conclusion

This work focuses on advancing the work of Paksoy et al., (2012) by developing a mixed integer nonlinear mathematical model that supports the SC node capacity decision so as to increase the effectiveness of the SCN as well as the line efficiency while minimizing the idle time (thanks to the incorporation of an upper limit for the cycle time and the minimization of the number of stations in the assembler). The model optimizes the SCN, consisting of manufacturers, assemblers and customers with the overall goal of minimizing the transportation costs for the concerned periods while balancing the assembly lines in assemblers in order to minimize the total cost of setting up stations concomitantly.

5.0. Future

The work presented is the first phase of the research which continues with the application of the model to real-life data to show its utility after which recommendations for its deployment will be made.

The model is expected to minimize the number of stations to be opened in the assembler as production rate increases which translates to reduction of activation costs of stations. In addition, enforcing a maximum limit of cycle times for all stations will ensure increase in the throughput rate of the line, that is, minimizing the idle time, thereby translating to increased line efficiency. Also, the overall transportation costs along the SCN network (Manufacturer – Assembler and Assembler – Customer) will be advantageously reduced.

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Biographies

Raji, Ibrahim .O. is a young scientist/scholar and currently a year 1 PhD student at LIUC – Carlo Cattaneo University, Italy. He earned his Bachelor of Science (B.Sc.) and Master of Science (M.Sc.) degrees in Industrial and Production Engineering department of Nigeria's Premier University, University of Ibadan, Nigeria. He also has an executive master's certification in Project Management from CUPE limited, United Kingdom. He has worked both in the industry (manufacturing sector specifically) and academic institutions as a lecturer in University of Ibadan, Nigeria and Kampala International University, Uganda.

His research interests majorly include performance and operations management (viz-a-viz productivity modelling and assessment), supply chain management and some element of discrete simulation. On these, he has participated in some projects at the University of Ibadan, Nigeria with articles published in academic journals. He is a Graduate Member of the Nigeria Society of Engineers (NSE).

Rossi, Tommaso is an Associate Professor of Mechanical Industrial Plants at the School of Engineering of LIUC - Cattaneo University. He is the Director of the Executive Program Leandustry 4.0 of LIUC Business School and the Lean Club of LIUC as well as Scientific Manager of i-FAB. He holds courses in operations at LIUC and Politecnico di Milano and is co-responsible for the lean and Industry 4.0 contents within the Executive Master "Global Supply Chain Management" at the IML-International Institute for the Management of Logistics (École Polytechnique Fédérale de Lausanne, College of Management of Technology).

His main themes of interest and research, on which he collaborates with MIT, Fraunhofer Institute and Dalle Molle Institute for Artificial Intelligence, are lean manufacturing, design of production systems, modelling and simulation of complex systems, data analytics. On these issues, he has been the coordinator of numerous projects commissioned by LIUC from leading national and international companies and author of more than 30 publications in international peer-reviewed journals.