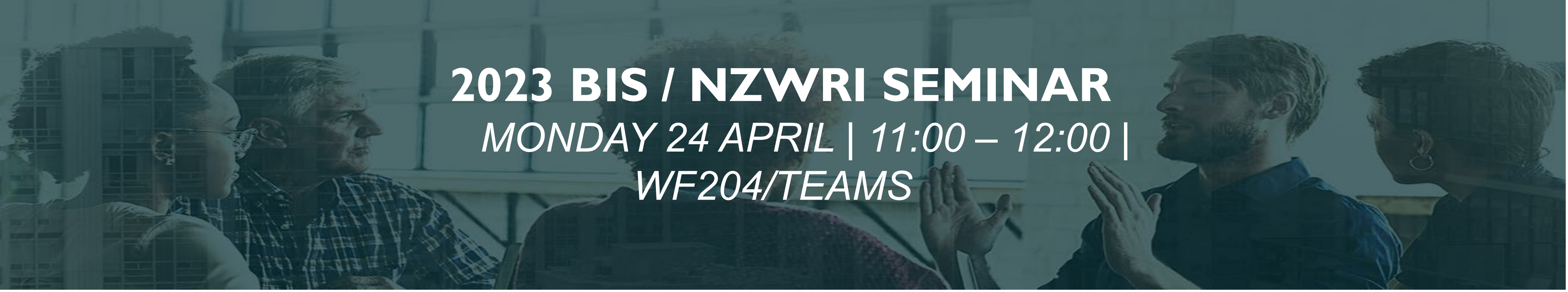


A new methodological approach for considering workers' diversity in assembly system design (by taking into account the European MAIA project)

Presenter: Niloofar Katiraee

1222·2022 800 ANNI

Università degli Studi di Padova

dtg Dipartimento di Tecnica e Gestione dei Sistemi Industriali

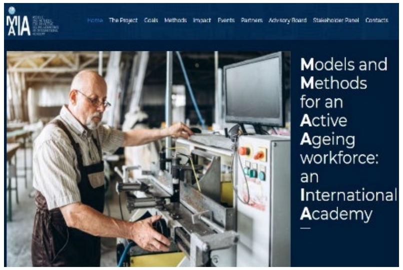
MAIA

www.maiaproject.eu

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 873077

Presentation agenda

1. Overview of the activities in the research group
2. MAIA project
3. Ph.D. thesis



DOCTORAL COURSE IN MECHATRONICS AND PRODUCT INNOVATION ENGINEERING

Ph.D. title: A new methodological approach for considering workers' diversity in assembly system design

Supervisor: Prof. Martina Calzavara*
Co-supervisors: Prof. Daria Battini* & Prof. Olga Battaïa**

Industrial Plants and Logistics group

* Department of Management and Engineering ,University of Padova
**Department of Operations Management and Information Systems, KEDGE Business School

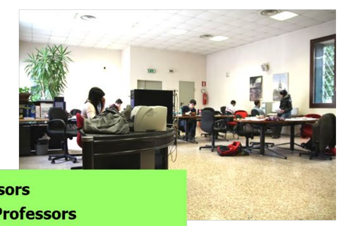
IN NUMBERS:

Year of foundation: 1222
Galileo Galilei professor in Padova: 1592 – 1610
>60,000 students

SCHOOL OF ENGINEERING:
> 4,000 new students each year
More than 20,000 students today
> 40 BA and MA courses of study

FIRST POSITION IN THE LAST NATIONAL EVALUATION OF RESEARCH QUALITY - VQR 2004-2010 and 2011-2014

In Industrial Engineering:
Padua University is 1st in Italy



- *23* Full Professors
- *29* Associate Professors
- *22* Assistant Professors
- *20* Staff
- *>60* Ph.D. students
- *15* Laboratories (12 research labs.)
- *>3000* Students today
- *3* BA and *4* MA courses of study

DIPARTIMENTO DI TECNICA E GESTIONE DEI SISTEMI INDUSTRIALI dtg

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Industrial plants and logistics group

SSD_ric	Istituzione	Somma punteggi (v)	# Prodotti attesi (·)	Valutazione media (I=v/n)	R (Profilo B)	Pos. grad. compl	Num. istituzioni compl	Quartile	Pos. grad. Quarti'
ING-IND/17	Bergamo	12,1	14	0,86	1,12	2	9	4	2
ING-IND/17	Bologna	16	20	0,8	1,03	5	9	4	5
ING-IND/17	Brescia	15,3	19	0,81	1,04	4	9	4	4
ING-IND/17	Castellanza LIUC	15	20	0,75	0,97	7	9	4	6
ING-IND/17	Milano Politecnico	42,7	51	0,84	1,08	3	9	4	3
ING-IND/17	Napoli Federico II	7,3	10	0,73	0,94	8	9	3	2
ING-IND/17	Padova	17,8	20	0,89	1,15	1	9	4	1
ING-IND/17	Palermo	10,1	14	0,72	0,93	9	9	4	7
ING-IND/17	Parma	7,8	10	0,78	1,01	6	9	3	1

Gruppo Padova
RANK 1°

Best Logistics Research Team of Italy (From 2004)

Prof. Persona Alessandro

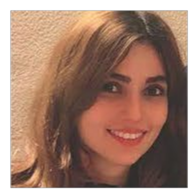
Prof.ssa Battini Daria

Prof. Faccio Maurizio

Prof.ssa Calzavara Martina

Ing. Zennaro Ilenia

Ing. Finco Serena

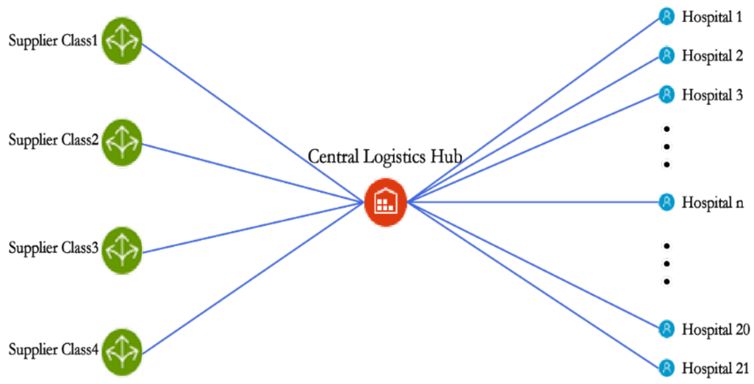


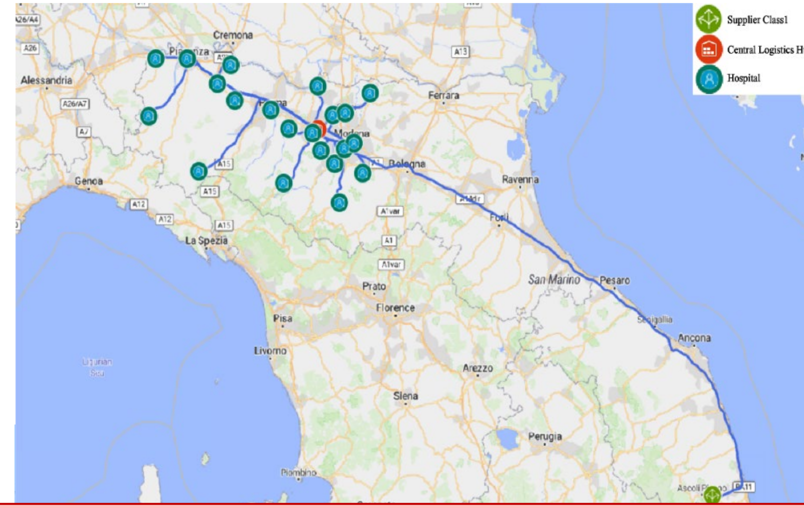
Ing. Katiraee Niloofar

Ing. Berti Nicola

Università degli Studi di Padova

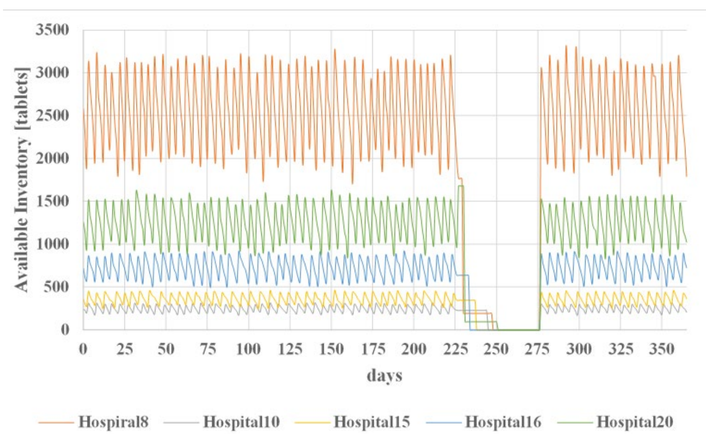
Analysis and design of resilient supply network systems

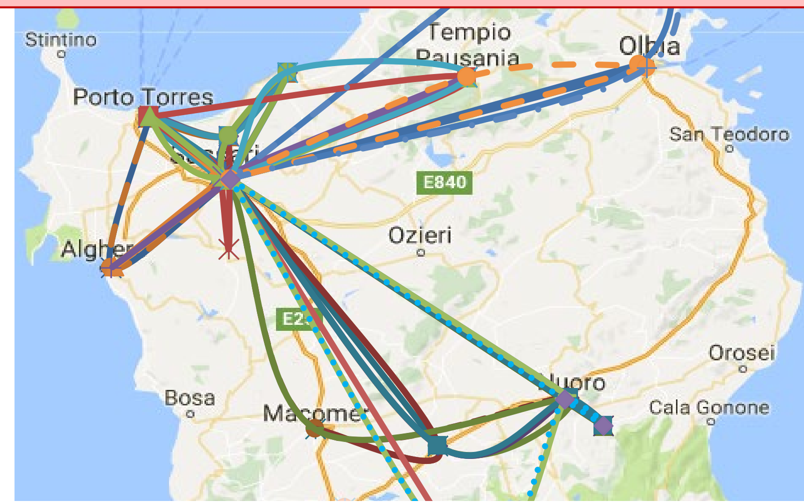




Central logistics hub design

Supply network simulation

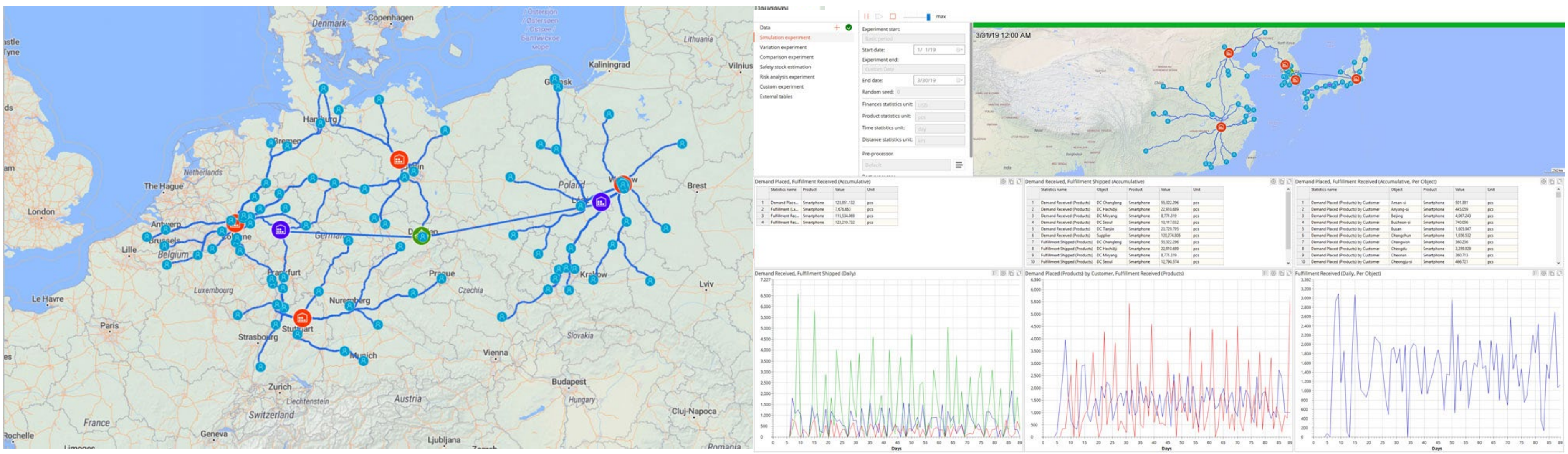




Analysis and design of resilient supply network systems

anyLogistix

anyLogistix is the supply chain analytics software to design, optimize and analyze your company's supply chain. It combines powerful analytical optimization approaches together with innovative simulation technologies offering you a comprehensive set of tools for end-to-end supply chain analytics.

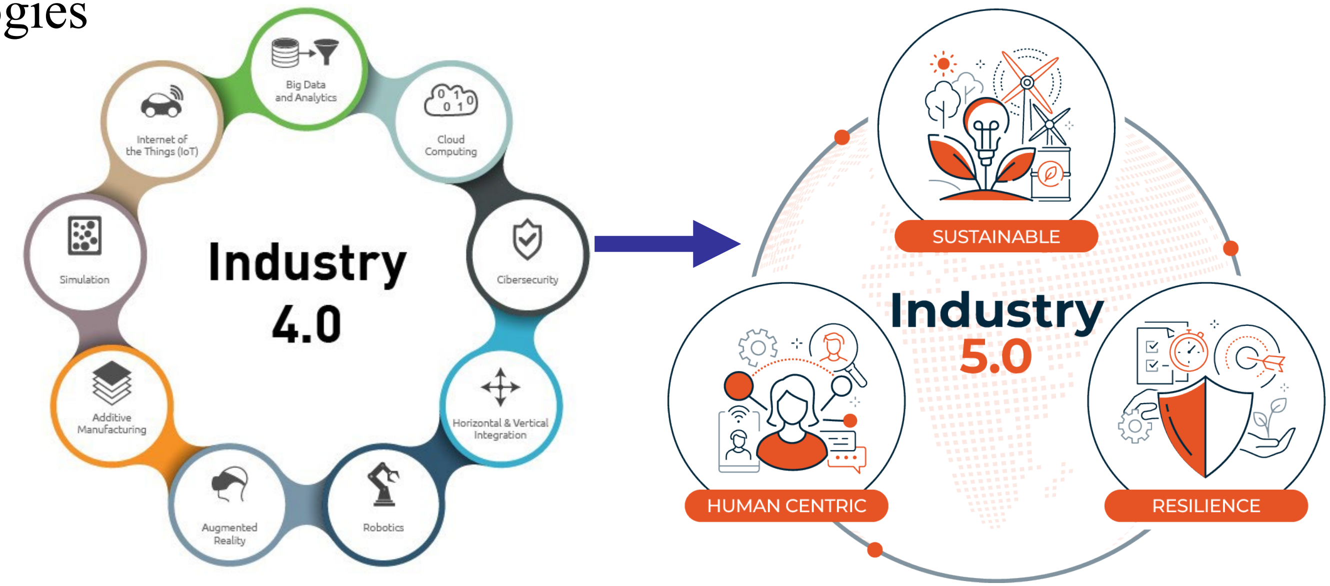


Digital ergonomic

How is digital technology influencing ergonomics, work design and risk mapping?

Industry 4.0 digital technologies

- Internet of Things (IoT)
- Cloud computing
- Big data
- Artificial intelligence
- Mixed reality (MR)
- Smart sensors
- Assistive devices



Workforce Ergonomics and Management Platform (WEM)

How is digital technology influencing ergonomics, work design and risk mapping?

WEM-Platform *aims to provide real-time postural risk assessment and feedback with insightful report made on-time and on-site.*

Exoskeletons

Exoskeletons are wearable devices designed for empowering human's biomechanical capabilities

Overhead assembly tasks

Construction and manufacturing tasks

No-overhead assembly tasks

Picking and material handling tasks

Exoskeleton & WEM

Investigating the impact of a back-support exoskeleton on worker productivity and ergonomics in order picking

European MAIA project

LinkedIn

International and multidisciplinary academy network focused on the aging workforce problem in manufacturing systems.

7 EU partners + 7 TC partners
Almost 1 million € funded
From 2020 to 2025

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 873077

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7 European partners

7 EUROPEAN PARTNERS: «BENEFICIARIES»

Project leader

1222·2022 800 ANNI

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Università degli Studi di Padova

OTH REGENSBURG

Ostbayerische Technische Hochschule Regensburg

University of Ljubljana

Univerza V Ljubljani

isae SUPAERO

Institut Superieur de l'Aeronautique et de l'espace

TECHNISCHE UNIVERSITÄT DARMSTADT

Technische Universitat Darmstadt

HWR

Hochschule für Wirtschaft und Recht Berlin

Berlin School of Economics and Law

Hochschule Fur Wirtschaft Und Recht Berlin

KEDGE

KEDGE BUSINESS SCHOOL

Groupe Kedge Business School

AUT AUCKLAND UNIVERSITY OF TECHNOLOGY NEW ZEALAND

7 third country partners

7 PARTNERS from CANADA, JAPAN, HONG KONG, NEW ZELAND, US

Keio University

The Chinese University of Hong Kong

University Of South Florida Board Of Trustees

The University of Auckland

Research Foundation Of The City University Of New York

Ryerson University

Auckland University of Technology

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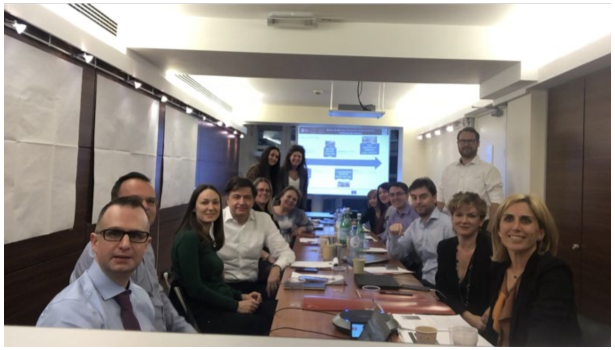
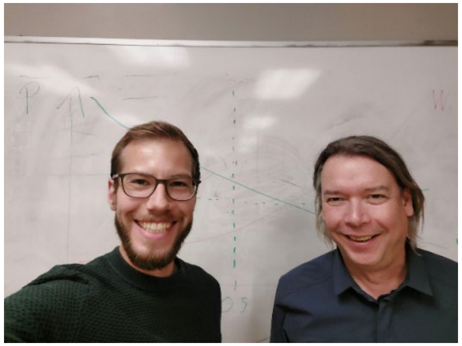
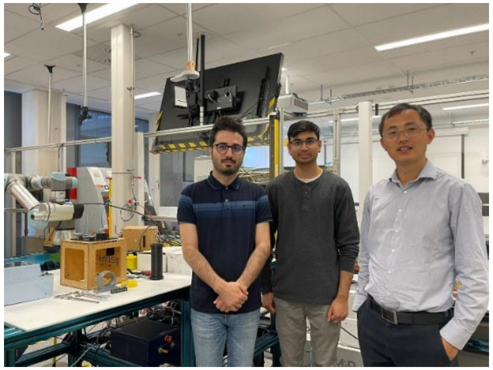
MAIA secondments







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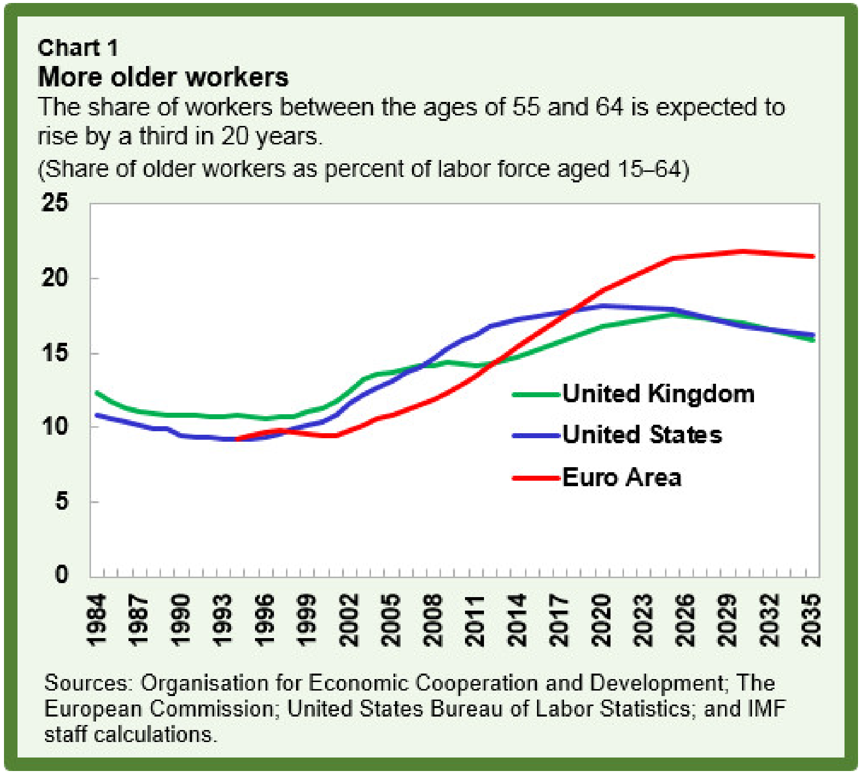
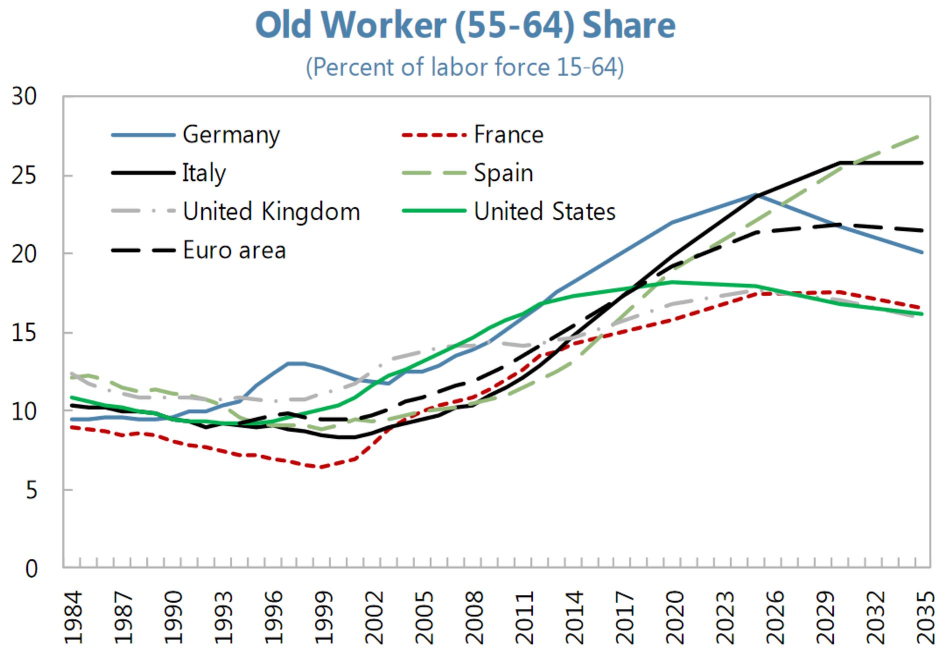
Labor force is aging





Sources: OECD; European Commission; BLS; and IMF staff calculations.

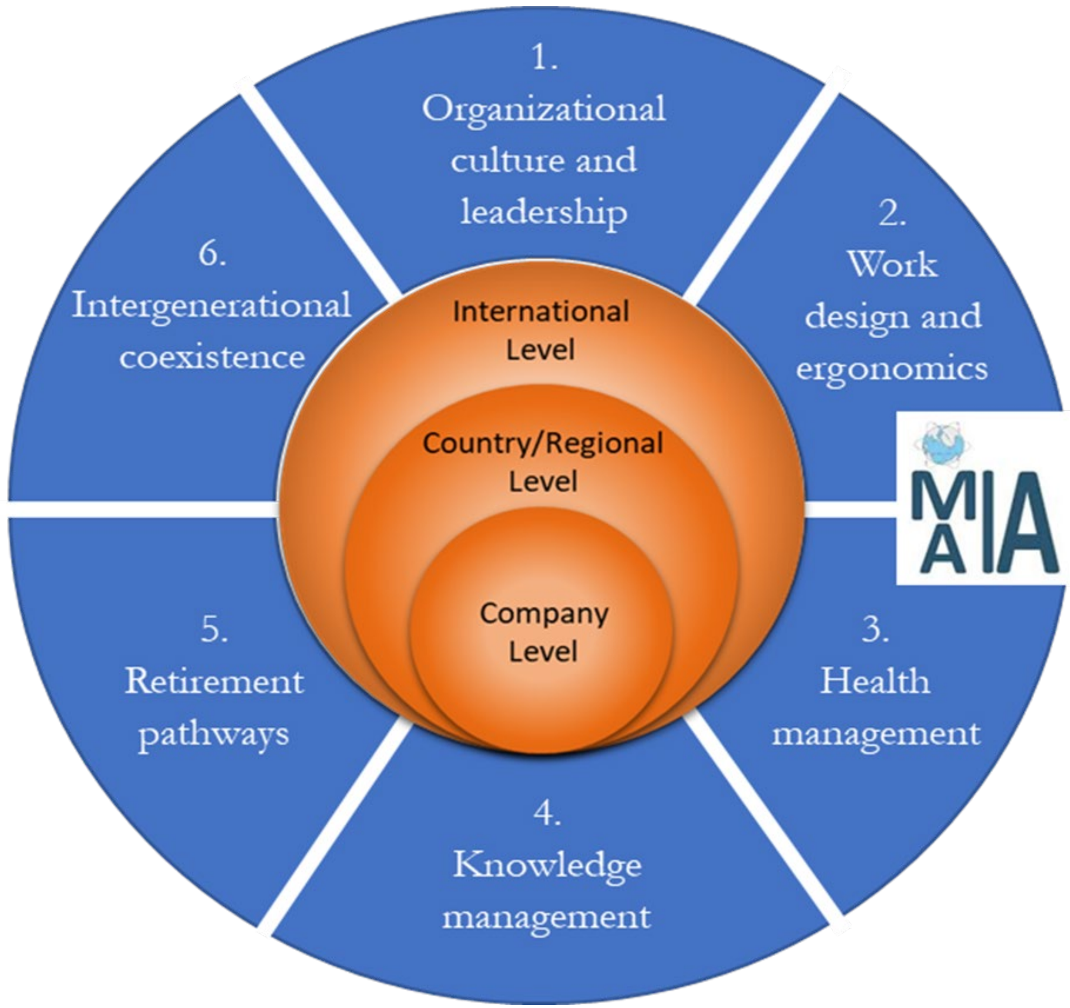
ISO 25550 Age-inclusive workforce

ISO 25550:2022 Ageing societies

General requirements and guidelines for an age-inclusive workforce

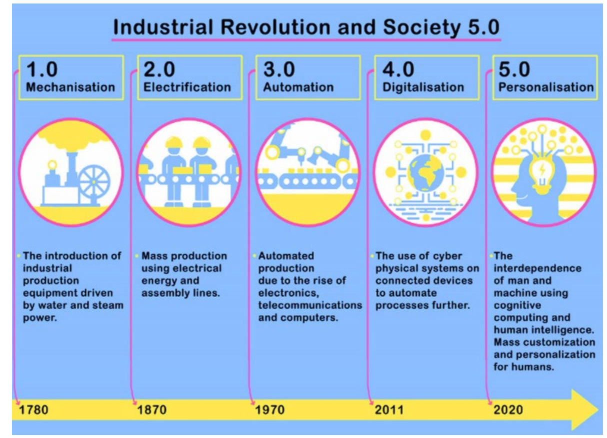
1. Workforce planning, re-entry, re-skilling
2. Age-friendly workspace
3. Individual health and wellbeing programs
4. Intergenerational collaboration and knowledge transfer and ageing-inclusive digital tools
5. Transition to retirement and continue working after retirement

The MAIA framework



Introduction

- ✓ Designing industrial operation systems more **human-centred**, **human-friendly**, and **sustainable** as also is recommended by Industry 5.0 paradigms.



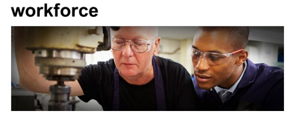
- ✓ **Assembly lines** are such of these manufacturing environments, since the presence of human workers is relevant, and the system performance largely relies on the **workers' efficiency** and motivation.

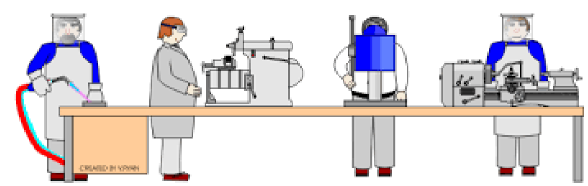
- ✓ Respond to **individuality**

ENTE ITALIANO DI NORMAZIONE

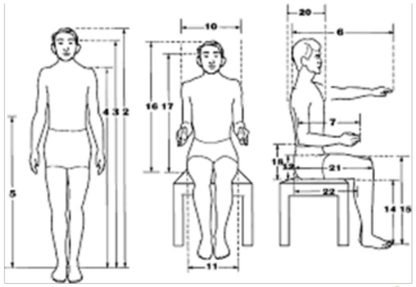
ISO 25550:2022 Ageing societies

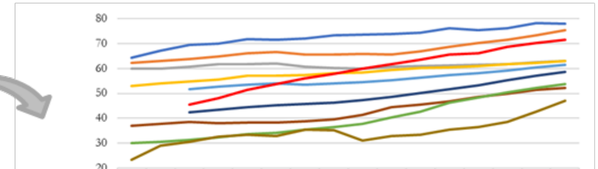
General requirements and guidelines for an age-inclusive workforce





Introduction





	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
New Zealand	64.3	67	69.5	70	71.8	71.6	72	73.2	73.6	73.8	74.3	76.2	75.3	76.2	78.3	78
Japan	62.2	63.1	63.9	64.7	66.2	66.5	65.7	65.5	65.9	65.5	66.9	68.7	70.1	71.6	73.4	75.3
United State	59.9	59.9	60.8	61.8	61.8	62.1	60.6	60.3	60	60.6	60.9	61.3	61.5	61.8	62.5	63.1
Canada	53	53.9	54.8	55.5	57	57.2	57.3	58.1	58.4	59.4	60.3	60.4	60.9	61.6	62.2	62.9
OECD			51.6	52.6	53.4	53.9	53.6	53.9	54.5	55.4	56.3	57.3	58.1	59.2	60.4	61.4
Germany			45.5	48.2	51.3	53.8	56.1	57.8	60	61.6	63.6	65.6	66.2	68.6	70.2	71.4
EU28			42.3	43.5	44.4	45.3	45.7	46.2	47.2	48.7	50.1	51.7	53.3	55.2	57.1	58.7
France	37	37.8	38.6	38.1	38.2	38.2	38.9	39.7	41.4	44.5	45.6	46.9	48.7	49.8	51.3	52.2
Italy	30.2	30.6	31.4	32.4	33.7	34.3	35.6	36.5	37.9	40.3	42.7	46.2	48.3	50.3	52.2	53.7
Slovenia	23.5	29	30.7	32.6	33.5	32.8	35.6	35.1	31.2	32.9	33.5	35.4	36.6	38.6	42.8	47.1

Employment rate by age group, 55-64 year-old (2003-2018)

Age

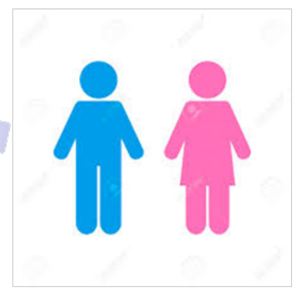
Anthropometry

Workers' differences

Gender

Skill

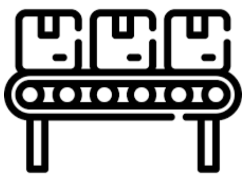
Personal and professional capabilities including the workers' learning rate, experience, competency, speed, motivation, capability or any particular physical attribute



Research scope

- Investigating **differences between workers** and how these differences can impact on the overall production systems.
- Developing **new optimization models** and **a methodological framework** in order to respond to **individual needs** in assembly systems.
- Using proposed approaches to increase the **workers' contribution** in **job assessment**.

Literature analysis

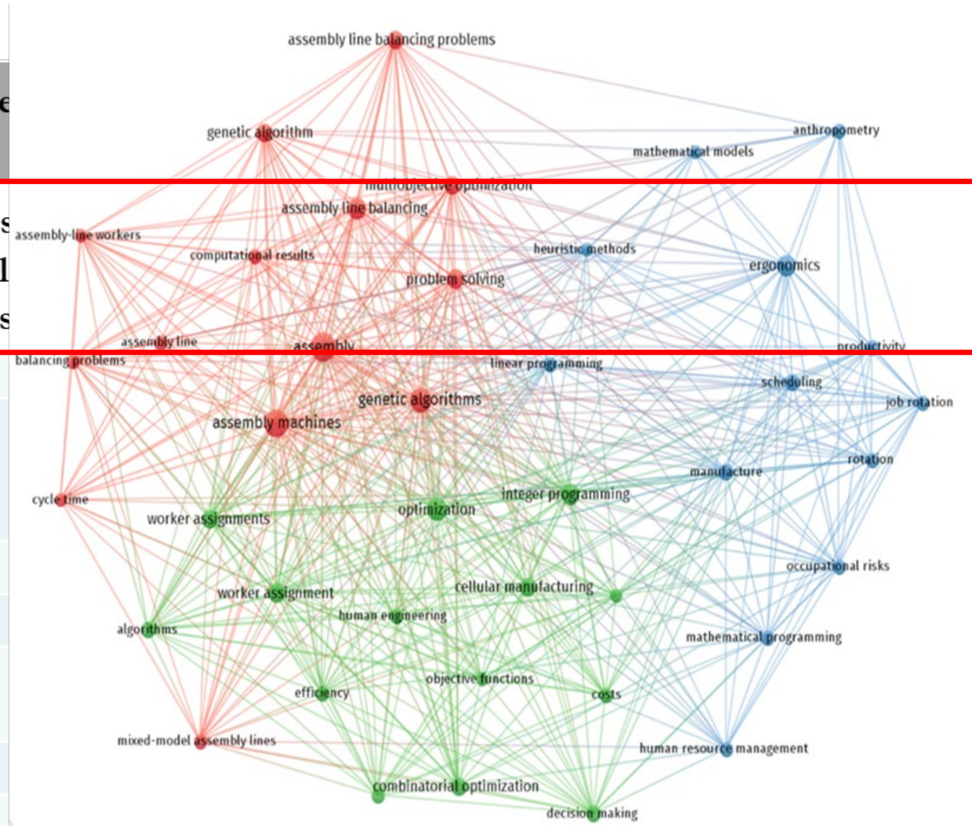
Scopus	Two sets of keywords	Selection Criteria
Workers' differences 	**1) Title**= "skilled-work*" OR "skill*" OR "age" OR "aging" OR "gender" OR "body and physical measure" OR "anthropometry" OR "human factor", OR "worker variability" OR "individual factor" OR "heterogenous worker*" OR "anthropology"	1. The focus has to be on a production setting and manufacturing sector 2. Included workers' differences measurements in modelling and design procedure
Problems under development 	**2) Title=** "assembly system" OR "assembly line*" OR "manual assembly line" OR "task assignment" OR "work assignment" OR "job assignment" OR "job schedule*" OR "task schedule*" OR "worker assignment" OR "worker allocation" OR "job rotation" OR "task switching" OR "job sequencing" OR "task sequencing" OR "work space design" OR "layout design" OR "workstation design" OR "facility location" OR "production system*" OR "manufacturing system*"	
7051 papers in initial search		**100 relevant papers**

Katiraee, N., Calzavara, M., Finco, S., Battini, D., & Battaïa, O. (2021). Consideration of workers' differences in production systems modelling and design: State of the art and directions for future research. ***International Journal of Production Research***, 1-32.

Literature analysis

How have the differences among workers been considered in manual production systems in previous studies?

Classification of the	Ass bal des	g space design and design
Human factors		
Skills		
personal and professional capabilities		1
Age		
Experience		-
Functional capacities		2
Gender		1
Anthropometry		5



Cluster analysis:

Red = "Assembly line" Green: "Worker assignment" Blue: "Job rotation"

Co-occurrence keywords network of the 100 selected papers

Literature analysis

What conclusions have been made regarding the impact of human variability on the performances of manual production systems?

Effect of human diversity factors on production system		
Effects from	**Effects on**	**Number of papers**
Skills		
	Cycle time / makespan time	20
	Task processing time / operation time	28
	Idle time	2
	Cost	13
	Labor cost	10
	Cross Training cost	9
	Throughput / Productivity / output/ line efficiency	17
	Workload balancing / smoothing	6
	Others: Energy expenditure, job safety and workers' health	3
Age		
	Cycle time; task processing time	3
	Experience	1
	Throughput / Productivity / output/ line efficiency	4
	Physical workload capacity / Fatigue or discomfort	4
Gender		
	Throughput / Productivity / output/ line efficiency	2
	Task processing time	1
	Physical workload capacity / Fatigue or discomfort	1
Anthropometry		
	Throughput / Productivity / output/ line efficiency	1
	Physical workload capacity / Fatigue or discomfort	1
	Others: Energy expenditure, job safety and workers' health	7

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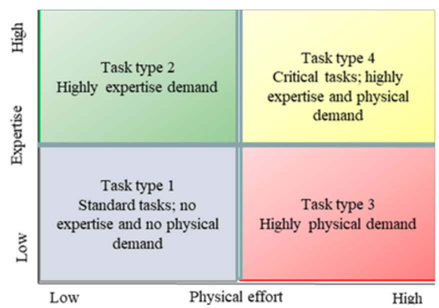
Mathematical models

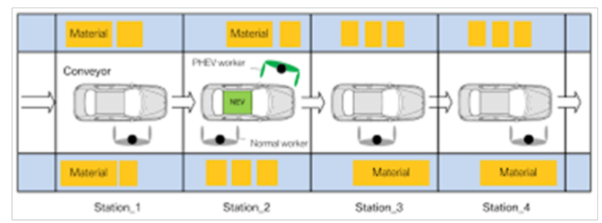
Model 1

Bi-Objective model by taking into account individual differences

Model 2

Single-Objective model by taking into account two sets of workers: trainers and assembler workers





Integrated model

Assembly Line Worker Assignment & Rebalancing Problem (ALWARBP)

Katiraee, N., Calzavara, M., Finco, S., Battini, D., (2021). Consideration of workforce differences in assembly line balancing and worker assignment problem. ***IFAC-INCOM***

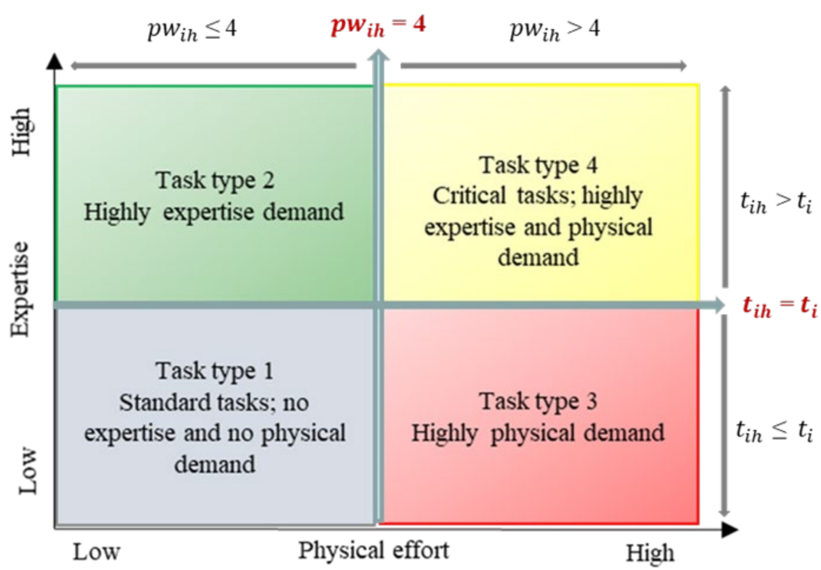
Katiraee, N., Finco, S., Battaia, O, Battini, D., (2021). Balancing assembly line with inexperienced and trainer workers: ***APMS international Conference, Advances in Prduction Management Systems.***

(1) Bi-Objective model by taking into account individual difference

Workers' differences

- Perceived physical exertion (measured by BORG Score); pw_{iw}
- Expertise (evaluated by task processing time); t_{iw}

$$pw_{iw}x_{ijw} \le 4 \quad \forall i \in I, \forall j \in J, \forall w \in W$$



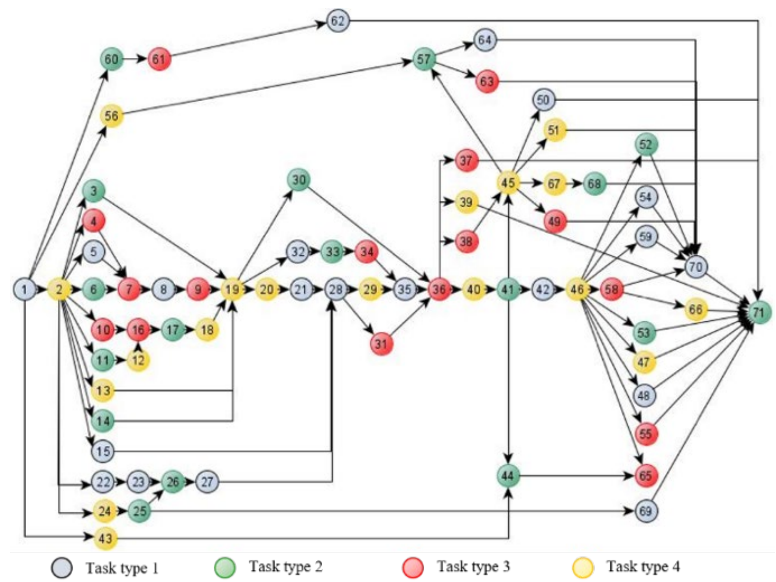
Worker-Task Categorization Matrix (WTCM)

Assembly Line Balancing and Worker Assignment Problem Type 2 Model (ALWABP-2)

Objective function:

$$\begin{aligned} &\text{Minimize} \quad ct \\ &\text{Minimize} \quad PES_{max} \end{aligned}$$

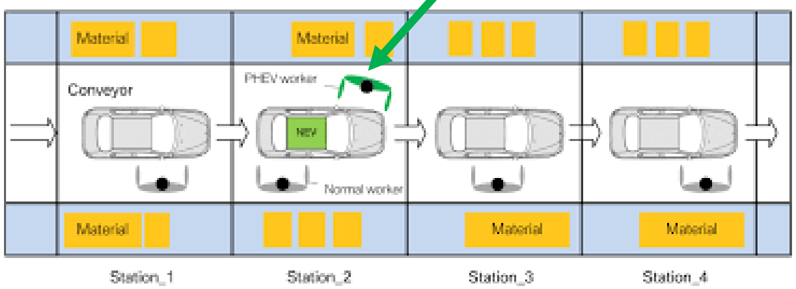
- **Cycle time**
- **Maximum perceived physical exertion**



Precedence constraints and tasks types for worker h

(2) Single-Objective model by taking into account two sets of workers: trainers (experienced) and assembler (inexperienced) workers

$$\overbrace{\sum_i \sum_w t_{ijw}}^{\text{Assemblers' contribution}} x_{ijw} - \underbrace{\sum_i \sum_t \acute{t}_{ijt} x'_{ijt}}_{\text{Trainers' contribution}} \le \boldsymbol{ct} \;\; \forall\, j = 1, .., \boldsymbol{J}$$



Assembly Line Balancing by taking into consideration the **assemblers (inexperienced)** and **trainers (experienced)** workers

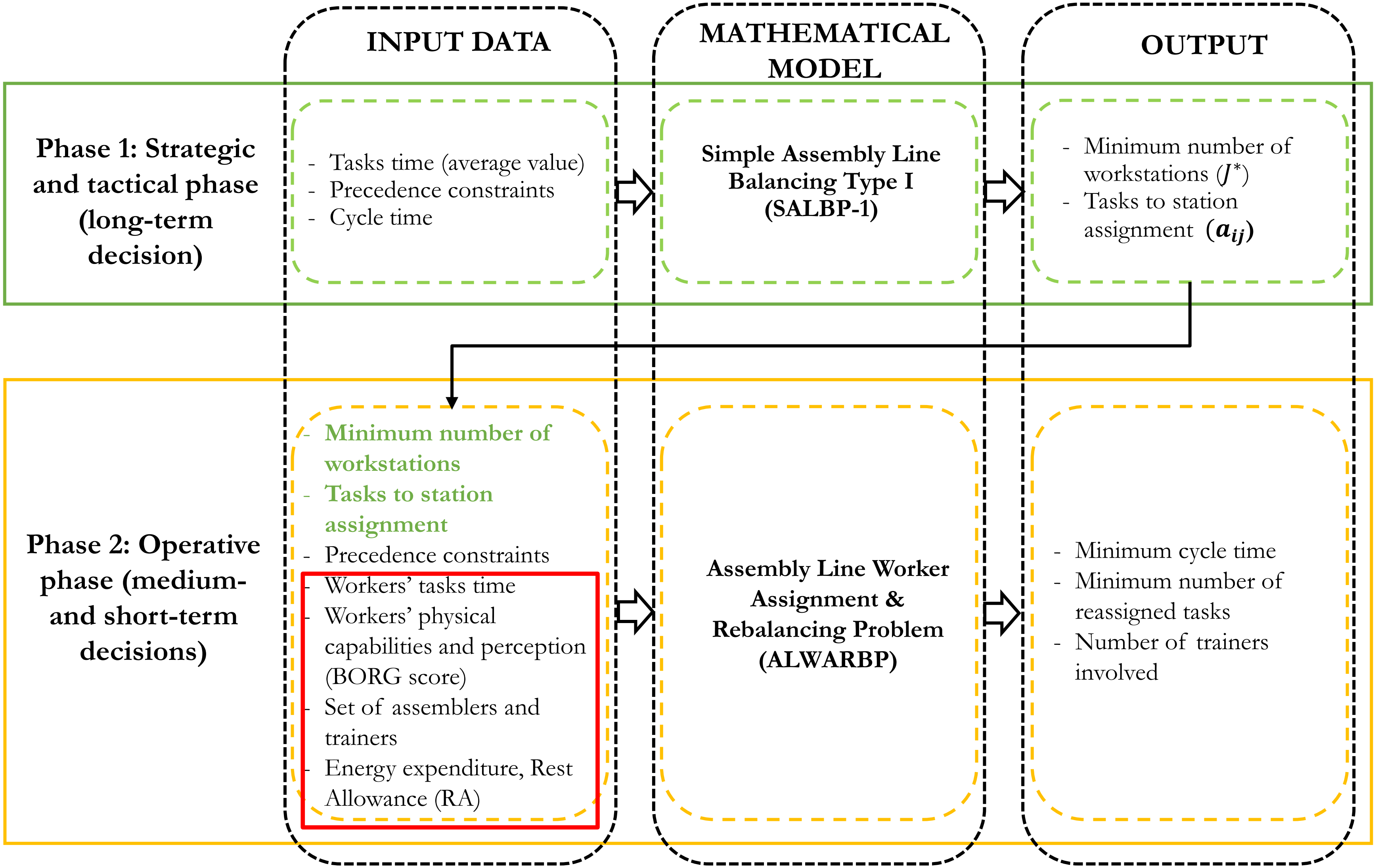
CW	Cost of assembler
CT	Cost of trainer
C_j	Cost of workstation

Objective function:

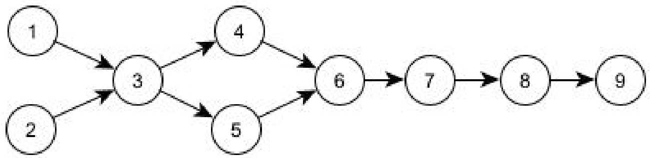
$$Minimize \quad Cost$$

$$Cost = \sum_j \left[\sum_t CT\acute{z}_{jt} + \sum_w CW z_{jw} + C_j y_j\right]$$

Integrated model



Integrated model

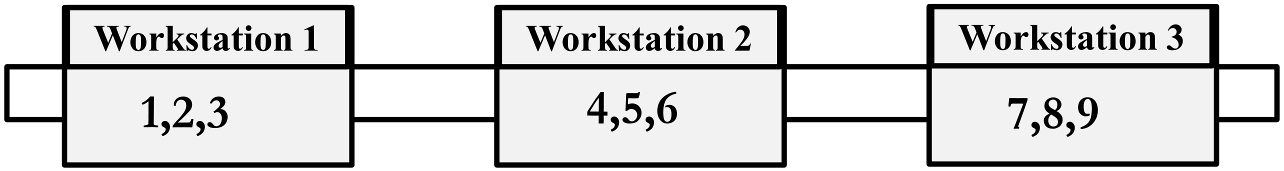


Task precedency, Task time, Cycle time

Objective function:

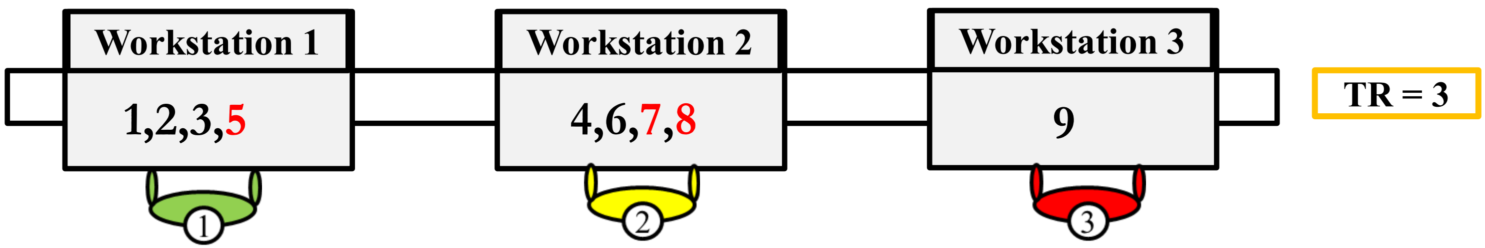
O.F.1: Minimize ct_1 (1)

O.F.2: Minimize TR=$\sum_i \sum_j q_{ij}$ (2)

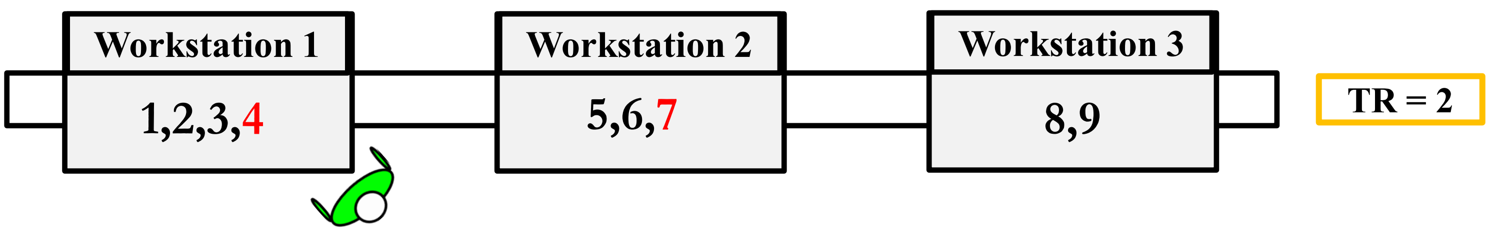


The initial balancing solution of the example problem (SALBP)

Workers' integration



Rebalancing solution of the example problem (ALWARBP)



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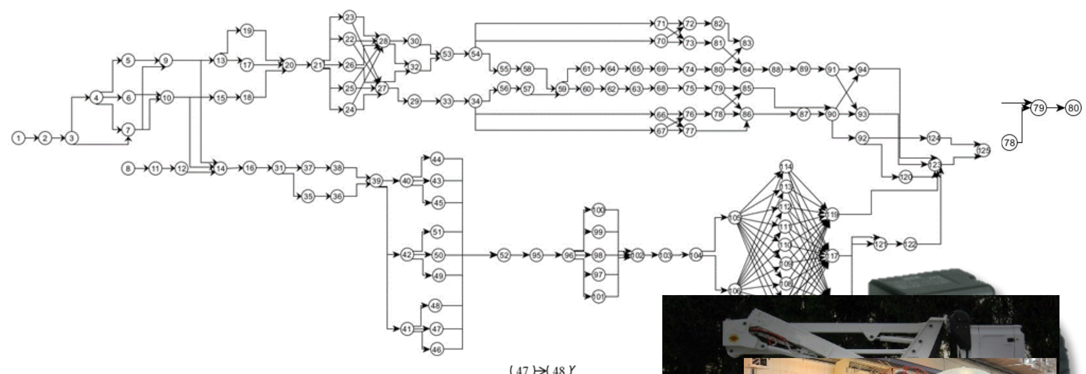
Model application in case studies

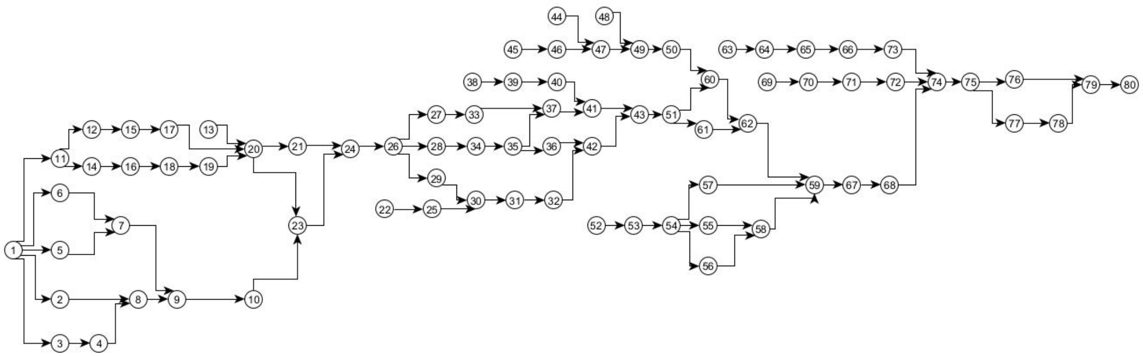
Case	1	2	3
Problem characteristics (size)	Small	Medium	Large
Number of tasks	50	80	125
Number of task precedencies	54	93	210
ct of the initial design (SALBP) [min/pc]	2.00	50.50	112.00
Number of workstations and assemblers	4	6	6
Number of experienced assemblers	1	-	1
Number of low experienced assemblers	2	3	2
Number of inexperienced assemblers	1	3	3
Number of trainers	1	2	2

- Small-size problem concerning the assembly of a jet pump
- Medium-size problem concerning the sub-assembly of a minibus
- Large-size problem concerning the sub-assembly of a business jet



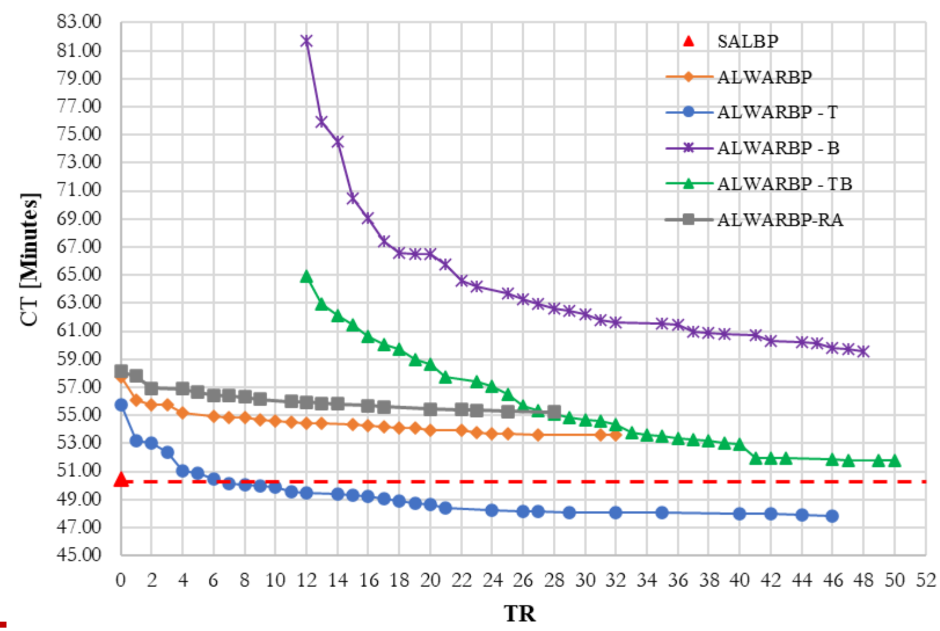
•Finishing

Model application in medium case



Case	2
Problem characteristics	Medium
Number of tasks	80
Number of task precedencies	93
CT of the initial design (SALBP) [min]	50.50
Number of workstations and assemblers	6
Number of experienced assemblers	-
Number of low experienced assemblers	3
Number of inexperienced assemblers	3
Number of trainers	2

Scenarios	Task time	Physical workload	Trainer	Rest Allowance (RA)
ALWARBP	×			
ALWARBP-T	×		×	
ALWARBP-B	×	×		
ALWARBP-TB	×	×	×	
ALWARBP-RA	×			×



Methodological approach

1. Initial design

1.1 Analysis

Information and data collection
Output: Available space, needed equipment, task precedencies, tasks time

1.2 Design

Assembly line balancing
Tools: SALBP-1
Output: Tasks assignment, Number of workstations

2. Workers' integration

2.1 Analysis

Job assessment
Tools: Analysts experience
Output: Jobs/tasks types

Workers' assessment
Tools: Analysts experience
Output: Workers' types

Workers involvement in job assessment

(1) Expertise (t_{iw})
Tools: Chronotechnics, MTM, MOST

(2) Perceived physical exertion (pw_{iw})
Tools: Borg scale, NASA-TLX

Output: Worker Task Categorization Matrix (*WTCM*)

Trainers' contribution evaluation
Tools: Chronotechnics, MTM, MOST,
Output: Tasks time variation

2.2 Design

Integration of workers differences in assembly line balancing
Tools: Model 1 (*ALWABP-2*)
Output: Pareto frontier (CT, PES_{max})

Integration of trainers in assembly line balancing
Tools: Model 2 (*ALWABP*)
Output: Total cost, number of trainers

2.3 Re-design

Integration of workers differences and trainers in assembly line re-balancing
Tools: Integrated model (*ALWARBP, ALWARBP-B, ALWARBP-T, ALWARBP-TB, ALWARBP-RA*)
Output: Pareto frontiers (TR, CT)

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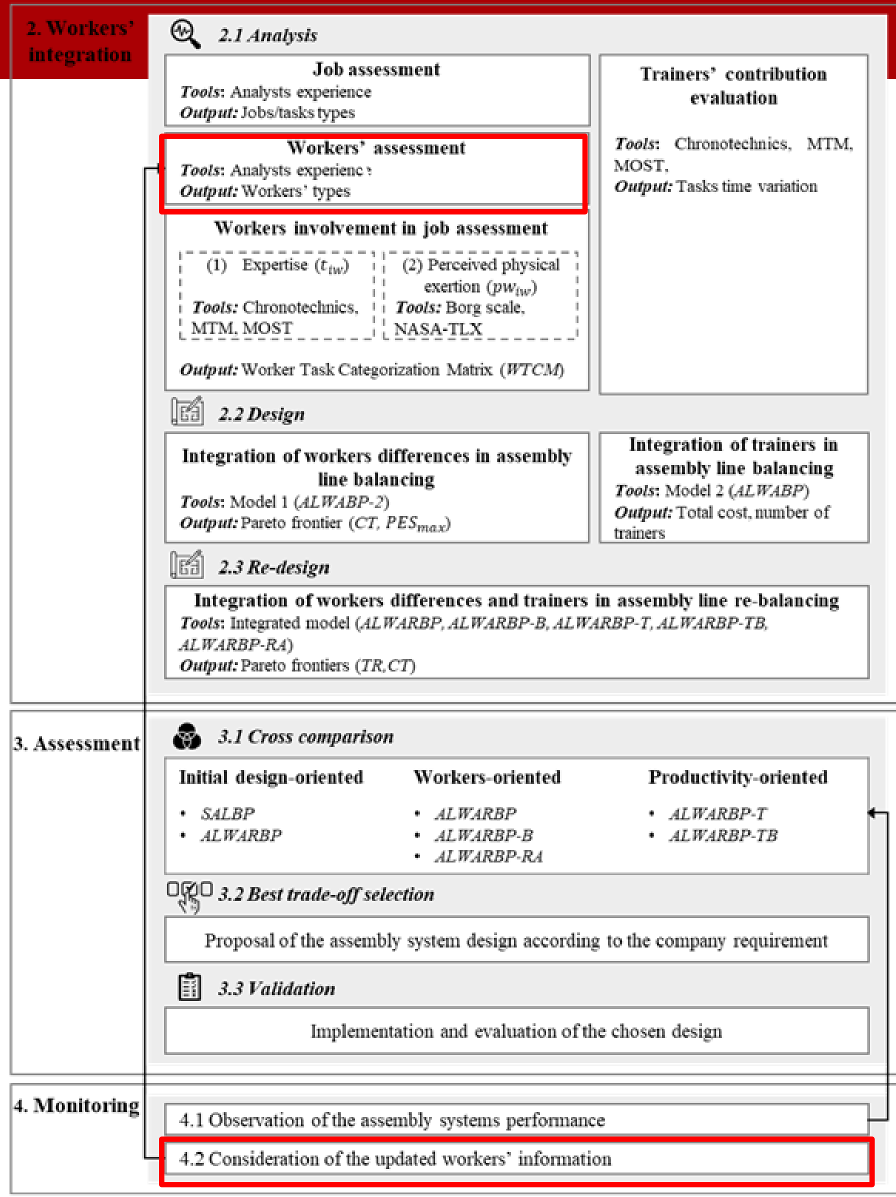
Methodological approach



List of papers

Publications in scientific journals

- Katiraee, N., Calzavara, M., Finco, S., Battini, D., & Battaïa, O. (2021). Consideration of workers' differences in production systems modelling and design: State of the art and directions for future research. ***International Journal of Production Research***, 1-32.

- Katiraee, N., Calzavara, M., Finco, S., Battaïa, O., & Battini, D. (2022). Assembly line balancing and worker assignment considering workers' expertise and perceived physical effort. ***International Journal of Production Research***, 1-21.

Conference proceeding

- Katiraee, N., Battini, D., Battaia, O., & Calzavara, M. (2019). Human diversity factors in production system modelling and design: state of the art and future researches. ***IFAC-PapersOnLine***, 52(13), 2544-2549.

- Katiraee, N., Berti, N., Calzavara, M., Finco, S. & Battini, D. (2020). The workforce ageing phenomenon: statistics, policies and practices. ***Proceedings of the Summer School Francesco Turco***.

- Katiraee, N., Calzavara, M., Finco, S., Battini, D., (2021). Consideration of workforce differences in assembly line balancing and worker assignment problem. ***IFAC-INCOM.***

- Katiraee, N., Finco, S., Battaia, O, Battini, D., (2021). Balancing assembly line with inexperienced and trainer workers: ***APMS international Conference, Advances in Prduction Management Systems.***

- Keshvarparast, A., Katiraee, N., Finco, S., Battini, D., (2021). Impacts of Cobots in manufacturing systems: literature review and open questions: *Proceedings of the Summer School Francesco Turco.*

- Battini, D., Finco, S., Katiraee, N., Grosse, E. H., & Glock, C. H. (2021). Active ageing workforce in manufacturing systems: an international discussion (No. 131506). ***Darmstadt Technical University, Department of Business Administration, Economics and Law, Institute for Business Studies (BWL).***

List of papers

Keshvarparast, A., Katiraee, N., Pirayesh, A., Battaia, O, Berti, N, (2023). Integrated Resource Optimization in a Multi-Product Separated Line Collaborative Assembly Line Balancing Problem (MPSLC-ALBP); Accepted in ***IFAC-PapersOnLine.***

Katiraee, N., Keshvarparast, A., Finco, S., Calzavara, M, (2023). Workforce individualization in Collaborative Assembly Line Re-Balancing; Accepted in ***27th International Conference on Production Research***

Martignago, M., Calzavara, M, Katiraee, N., Ivanov, D, Battini, D (2023). Investigating the effects of different actions on the resilience of a supply chain: a case study. Accepted in ***27th International Conference on Production Research***

Thank you for your attention

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University of Padua – ITALY

Model 1

Model 1

$$\text{Minimise} \quad ct \tag{1}$$

$$\text{Minimise} \quad PES_{max} \tag{2}$$

$$\sum_j \sum_w x_{ijw} = 1, \forall\, i = 1,..,I \tag{3}$$

$$\sum_j z_{jw} \leq 1 \;\forall\, w = 1,..,W \tag{4}$$

$$x_{ijw} \leq z_{jw}, \forall\, i = 1,..,I; \forall\, j = 1,..,J, \forall\, w = 1,..,W \tag{5}$$

$$\sum_j \sum_w j x_{ijw} \leq \sum_j \sum_w j x_{kjw}\,, \forall (i,k) \in A \tag{6}$$

$$\sum_i \sum_w t_{iw}\, x_{ijw} \leq ct \quad \forall\, j = 1,..,J \tag{7}$$

$$\sum_i \sum_w pw_{iw}\, x_{ijw} \leq PES_{max} \quad \forall\, j = 1,..,J \tag{8}$$

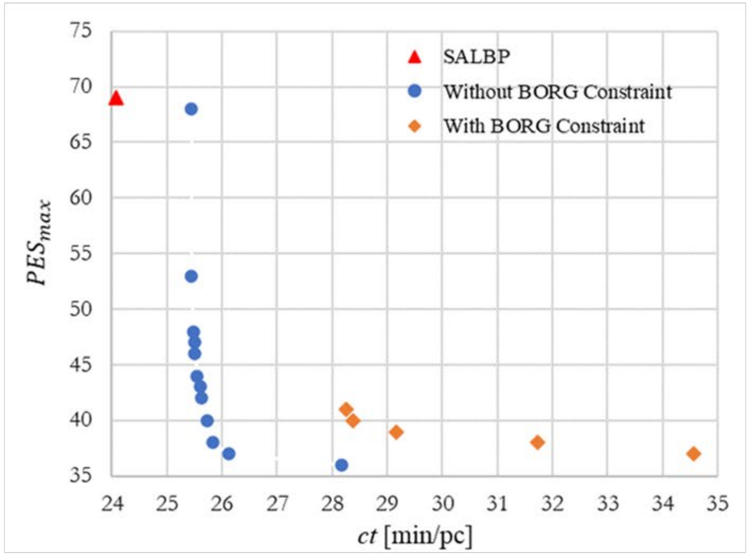
$$x_{ijw} \in \{0;1\} \;\forall\, i = 1,..,I; \forall\, j = 1,..,J, \forall\, w = 1,..,W \tag{9}$$

$$z_{jw} \in \{0;1\} \;\forall\, j = 1,..,J, \forall\, w = 1,..,W \tag{10}$$

$$ct \in \mathbb{R}^+ \tag{11}$$

$$PES_{max} \in \mathbb{R}^+ \tag{12}$$

Model application in case study



Model 1_results

Point	ct PES_{max}	Workstation time [min] PES						Workstation maximum Borg score Workstation weighted Borg score					
		1	2	3	4	5	6	1	2	3	4	5	6
1	**25.44** **68**	25.26 66	**25.44** 45	**25.44** 29	25.40 21	25.42 20	25.43 **68**	5 4.0	3 2.7	4 3.8	7 2.1	3 2.8	6 5.1
2	**25.45** **53**	25.39 **53**	25.45 52	25.44 29	25.38 12	**25.45** 43	**25.45** 38	5 4.0	3 2.7	4 3.8	4 2.0	3 3.0	6 4.8
3	**25.48** **48**	25.36 **48**	25.37 42	25.46 38	**25.48** 25	25.33 43	25.42 35	6 4.9	3 2.8	4 3.7	7 1.9	3 3.0	5 4.0
4	**25.50** **47**	25.16 44	**25.50** 36	25.42 **47**	25.48 25	25.46 45	25.42 35	6 4.9	3 2.8	4 3.7	7 1.9	3 3.0	5 4.0
5	**25.51** **46**	25.26 **46**	**25.51** 39	25.47 **46**	25.48 25	25.48 32	25.46 **46**	5 4.2	3 2.8	4 3.8	7 1.9	3 2.7	6 5.2
6	**25.55** **44**	25.16 **44**	**25.55** 42	25.51 38	25.48 25	25.49 42	25.54 39	6 4.9	3 2.8	3 3.7	7 1.9	3 2.9	5 4.0
7	**25.61** **43**	**25.61** **43**	25.59 **43**	25.49 **43**	25.52 25	**25.61** 35	25.58 40	5 4.3	3 2.7	4 3.8	4 2.2	3 2.7	6 5.0
8	**25.62** **42**	25.60 **42**	25.61 41	**25.62** **42**	**25.62** 34	25.58 35	25.61 40	5 4.3	3 2.7	4 3.7	7 2.4	3 2.7	6 5.0
9	**25.72** **40**	**25.72** 38	25.65 38	25.71 36	25.57 **40**	25.68 39	25.57 39	6 4.8	3 2.7	3 2.7	5 4.0	7 2.5	4 3.8
10	**25.74** **39**	25.72 38	25.69 **39**	25.67 35	**25.74** 38	**25.74** **39**	25.70 **39**	6 4.8	3 2.8	3 2.7	5 3.9	4 2.5	4 3.8
11	**25.84** **38**	25.72 **38**	**25.84** **38**	**25.84** **38**	25.70 36	25.69 **38**	25.72 **38**	6 4.8	3 2.7	3 2.7	5 4.0	4 3.7	4 2.7
12	**26.12** **37**	25.98 **37**	25.98 **37**	25.82 36	**26.12** 36	25.91 **37**	25.72 **37**	4 2.9	3 2.8	6 5.6	5 3.7	4 3.9	3 2.3
13	**28.16** **36**	**28.16** **36**	27.39 35	28.10 **36**	23.96 **36**	23.88 **36**	24.04 **36**	3 2.6	4 3.0	3 2.8	6 4.5	4 3.7	5 4.1

Point	ct PES_{max}	Workstation time [min] PES						Workstation maximum Borg score Workstation weighted Borg score					
		1	2	3	4	5	6	1	2	3	4	5	6
1	**28.25** **41**	28.23 **41**	**28.25** 40	28.09 37	20.83 25	28.12 36	17.40 40	4 2.69	3 2.85	4 3.82	4 3.21	3 3	4 4
2	**28.37** **40**	28.36 38	27.91 **40**	**28.37** **40**	23.82 28	28.12 36	15.41 36	4 2.65	3 2.76	4 3.81	4 4	3 2.89	4 3.31
3	**29.17** **39**	27.61 37	28.78 38	28.41 37	23.82 28	**29.17** **39**	15.41 36	3 2.50	4 3.06	4 3.48	4 4	3 3	4 3.31
4	**31.73** **38**	31.59 **38**	30.56 **38**	9.45 36	31.64 37	**31.73** **38**	15.418 36	3 2.52	4 3.46	4 4	3 2.67	4 3.78	4 3.31
5	**34.57** **37**	29.536 **37**	**34.57** **37**	10.166 36	23.85 **37**	33.9 **37**	17.84 36	4 2.79	3 2.89	4 4	4 3.47	3 2.83	4 3.40

Model 2

Model 2

$$\text{Minimise} \quad Cost = \sum_j \left[\sum_t CT\acute{z}_{jt} + \sum_w CWz_{jw} + C_j v_j\right] \qquad \boxed{(1)}$$

$$\sum_j \sum_w x_{ijw} = 1, \forall\, i = 1,..,I \qquad (2)$$

$$\sum_t \acute{x}_{ijt} \le \sum_w x_{ijw} \quad \forall\, i = 1,..,I; \forall\, j = 1,..,J \qquad (3)$$

$$x_{ijw} \le z_{jw}, \forall\, i = 1,..,I; \forall\, j = 1,..,J, \forall\, w = 1,..,W \qquad (4)$$

$$\acute{x}_{ijt} \le z'_{jt}, \forall\, i = 1,..,I; \forall\, j = 1,..,J, \forall\, t = 1,..,T \qquad (5)$$

$$\sum_w z_{jw} \le v_j, \forall\, j = 1,..,J \qquad (6)$$

$$\sum_j \sum_w j x_{ijw} \le \sum_j \sum_w j x_{kjw}, \forall (i,k) \in A \qquad (7)$$

$$\sum_i \sum_w \acute{t}_{ijt} x_{ijw} - \sum_i \sum_t \acute{\acute{t}}_{ijt} \acute{x}_{ijt} \le ct * v_j \;\forall\, j = 1,..,J \qquad \boxed{(8)}$$

$$\sum_j z_{jw} \le 1 \;\forall\, w = 1,..,W \qquad (9)$$

$$\sum_w z_{jw} \le 1 \;\forall\, j = 1,..,J \qquad (10)$$

$$\sum_j \acute{z}_{jt} \le 1 \;\forall\, t = 1,..,T \qquad (11)$$

$$\sum_t \acute{z}_{jt} \le 1 \;\forall\, j = 1,..,J \qquad (12)$$

$$x_{ijw} \in \{0;1\} \;\forall\, i = 1,..,I; \forall\, j = 1,..,J, \forall\, w = 1,..,W \qquad (13)$$

$$\acute{x}_{ijt} \in \{0;1\} \;\forall\, i = 1,..,I; \forall\, j = 1,..,J, \forall\, t = 1,..,T \qquad (14)$$

$$z_{jw} \in \{0;1\} \;\forall\, j = 1,..,J, \forall\, w = 1,..,W \qquad (15)$$

$$z'_{jt} \in \{0;1\} \forall\, j = 1,..,J, \forall\, t = 1,..,T \qquad (16)$$

$$v_j \in \{0;1\} \qquad (17)$$

Model application in case study

The results of the applied model with and without consideration of trainers

ct [min/pc]	Cost	Number of trainer workers	Number of assembler workers	Number of Open stations	Station time [ST_j]
35	18.6	2	4	4	[34.904, 34.727, 34.959, 34.835]
	23	0	5	5	[34.918, 34.908, 34.377, 34.897, 34.939]
40	17.3	1	4	4	[39.872, 38.774, 39.989, 39.581]
	20	0	5	5	[33.603, 39.391, 39.669, 36.656, 37.956]
45	14.6	2	3	3	[44.62, 44.453, 43.863]
	16	0	4	4	[44.89, 44.418, 44.994, 44.968]
50	13.3	1	3	3	[49.858, 49.973, 49.963]
	16	0	4	4	[45.995, 43.145, 49.737, 44.922]
55	13.3	1	3	3	[54.378, 54.638, 51.904]
	16	0	4	4	[46.972, 41.824, 54.255, 46.23]
60	12	0	3	3	[59.732, 59.883, 59.154]
	12	0	3	3	[59.678, 59.942, 59.84]

Integrated model

$$\text{Minimise} \quad ct_1 \tag{1}$$

$$\text{Minimise} \quad TR = \sum_i \sum_j q_{ij} \tag{2}$$

$$\sum_j \sum_w x_{ijw} = 1, \forall i = 1,..,I \tag{3}$$

$$\sum_t \acute{x}_{ijt} \le \sum_w x_{ijw} \quad \forall i = 1,..,I; \forall j = 1,..,J^* \tag{4}$$

$$x_{ijw} \le z_{jw}, \forall i = 1,..,I; \forall j = 1,..,J^*, \forall w = 1,..,W \tag{5}$$

$$\acute{x}_{ijt} \le z'_{jt}, \forall i = 1,..,I; \forall j = 1,..,J, \forall t = 1,..,T \tag{6}$$

$$\sum_j \sum_w j x_{ijw} \le \sum_j \sum_w j x_{kjw}, \forall (i,k) \in A \tag{7}$$

$$\sum_i \sum_w t_{iw} x_{ijw} - \sum_i \sum_t tt_{it} \acute{x}_{ijt} \le ct_1 \ \forall j = 1,..,J^* \tag{8}$$

$$\sum_j z_{jw} \le 1 \ \forall w = 1,..,W \tag{9}$$

$$\sum_w z_{jw} \le 1 \ \forall j = 1,..,J^* \tag{10}$$

$$\sum_j \acute{z}_{jt} \le 1 \ \forall t = 1,..,T \tag{11}$$

$$\sum_t \acute{z}_{jt} \le 1 \ \forall j = 1,..,J^* \tag{12}$$

$$q_{ij} \ge \sum_w x_{ijw} - \boxed{a_{ij}} \ \forall i = 1,..,I; \forall j = 1,..,J^* \tag{13}$$

$$x_{ijw} \in \{0;1\} \ \forall i = 1,..,I; \forall j = 1,..,J^*, \forall w = 1,..,W \tag{14}$$

$$\acute{x}_{ijt} \in \{0;1\} \ \forall i = 1,..,I; \forall j = 1,..,J^*, \forall t = 1,..,T \tag{15}$$

$$z_{jw} \in \{0;1\} \ \forall j = 1,..,J^*, \forall w = 1,..,W \tag{16}$$

$$z'_{jt} \in \{0;1\} \forall j = 1,..,J^*, \forall t = 1,..,T \tag{17}$$

$$q_{ij} \in \{0;1\} \forall i = 1,..,I, \forall j = 1,..,J^* \tag{18}$$

$$ct_1 \in \mathbb{R} \tag{19}$$

$$TR \in \mathbb{N} \tag{20}$$

(1) ⇨ **Minimization of cycle time**

(2) ⇨ **Minimization of number of reassigned tasks among workstations**

(8) ⇨ **Trainer's contribution**

(13) ⇨ **Calculating the number of reassigned tasks respecting to the initial design**

Linearization

$$\left(1 + RA_j\right)\sum_i \sum_w t_{iw}\, x_{ijw} \le ct_1 \;\forall\, j = 1,..,J^*$$

$$RA_j = max\left\{0\,;\, \frac{\frac{\sum_i \sum_w x_{ijw}\, e_i}{\sum_i \sum_w x_{ijw}\, t_{iw}} - MAEE_w}{MAEE_w - ET_R}\right\} \;\forall\, j = 1,..,J^*$$

RA_j	Rest Allowance
e_i	Energy required to process task *i*
$MAEE_w$	Maximum Acceptable Energy Expenditure for assembler *w*
ET_R	Rest Energy-Time ratio (1.86 kcal/min)

MAEE = 0.0016 [(60-0.55 AGE) BW eSilva et al. (2016)

$$N_i = \max\{0;\textstyle\sum_i \sum_w x_{iiw}\,(e_i - t_{iw} * MAEE_w)\} \;\forall\, j = 1,..,J^*$$

$$N_j \ge 0 \;\;\forall\, j = 1,..,J^*$$

$$N_j \ge \textstyle\sum_i \sum_w x_{ijw}\,(e_i - t_{iw} * MAEE_w) \;\;\forall\, j = 1,..,J^*$$

$$N_j \le UB\gamma_j \;\;\forall\, j = 1,..,J^*$$

$$N_j \le \textstyle\sum_i \sum_w x_{ijw}\,(e_i - t_{iw} * MAEE_w) + UB(1-\gamma_j) \;\;\forall\, j = 1,..,J^*$$

$$N_j = \textstyle\sum_i \sum_w r_{ijw}\,(MAEE_w - ET_R) * t_{iw} \;\;\forall\, j = 1,..,J^*$$

$$\gamma_j \in \{0,1\} \;\;\forall\, j = 1,..,J^*$$

$$N_j \in \mathbb{R}^+ \;\;\forall\, j = 1,..,J^*$$

$$r_{ijw} \le UB * x_{ijw} \;\;\forall\, i = 1,..,I,\; \forall\, j = 1,..,J^*, \forall\, w = 1,..,W$$

$$r_{ijw} \le RA_j \;\;\forall\, i = 1,..,I, \forall\, j = 1,..,J^*, \forall\, w = 1,..,W$$

$$r_{ijw} \ge RA_j - UB(1 - x_{ijw}) \;\;\forall\, i = 1,..,I,\; \forall\, j = 1,..,J^*, \forall\, w = 1,..,W$$

$$r_{ijw} \in \mathbb{R}^+ \;\;\forall\, i = 1,..,I,\; \forall\, j = 1,..,J^*, \forall\, w = 1,..,W$$

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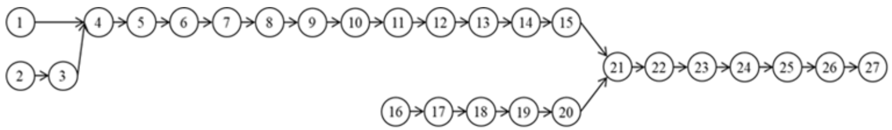
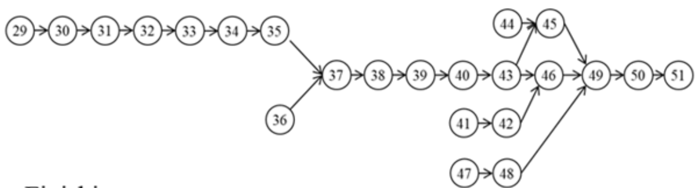
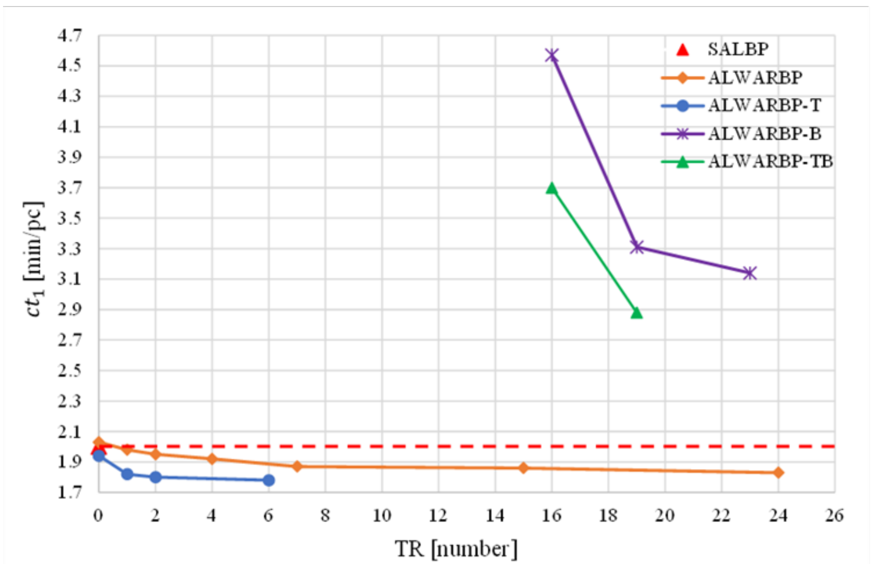
Integrated model application in small case

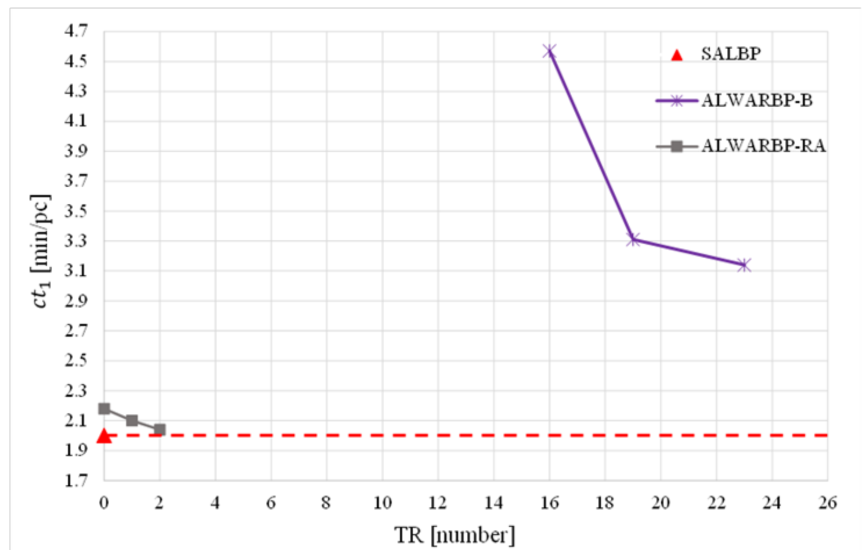


•Preassembly

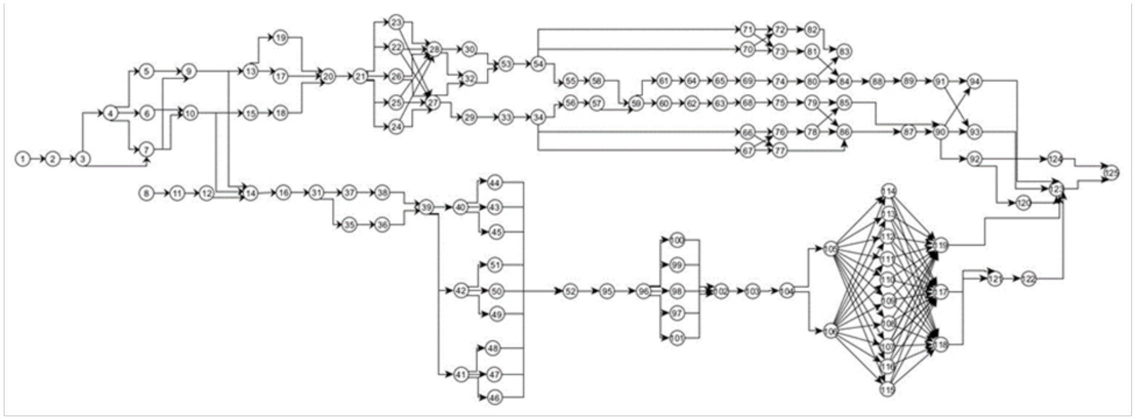


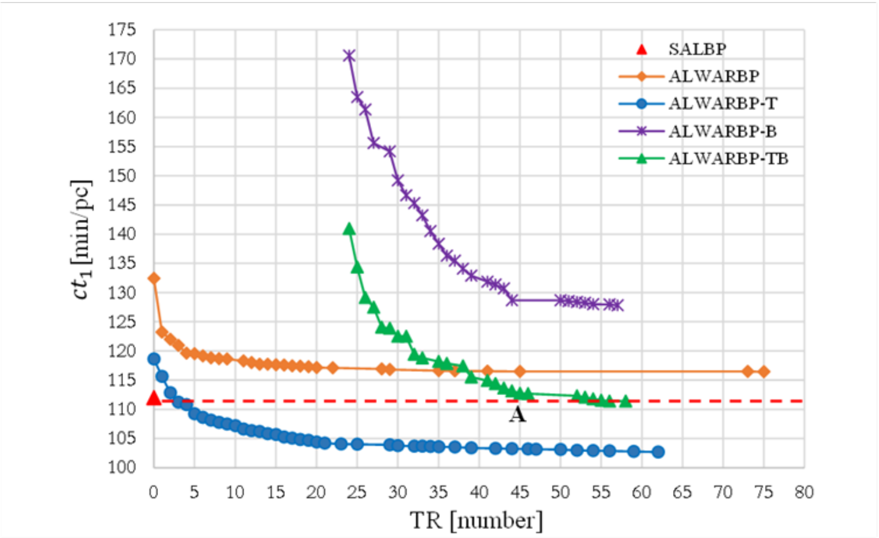
•Finishing

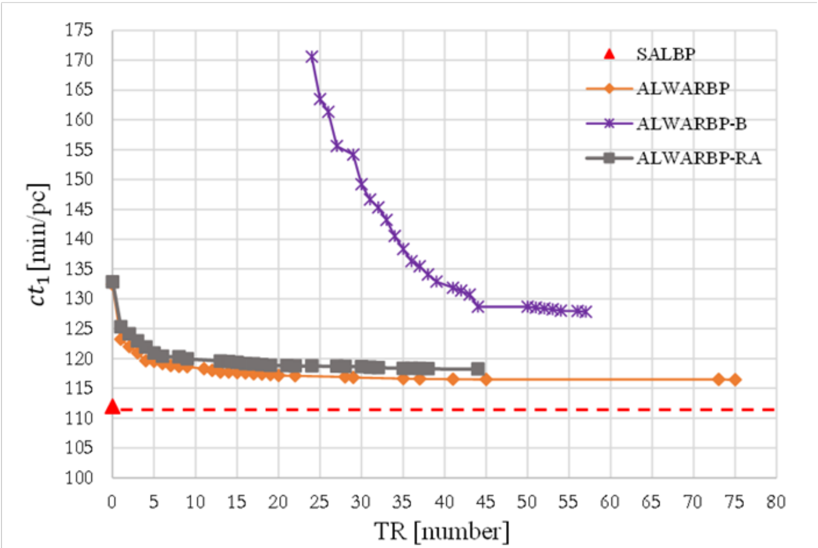




Integrated model application in large case







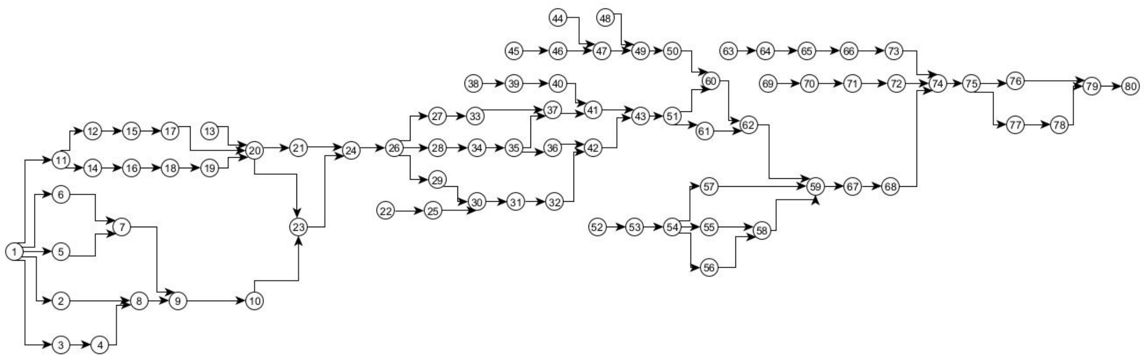
Computation time

Computation times of some instances of the three real cases

- The three optimisation model applications have been solved using the **IBM ILOG CPLEX 20.1.0** software set to the default parameters.
- The computational experiments were conducted using a computer with an **Intel (R) Core™ i7-8550U 1.8 GHz and 16 GB RAM**.

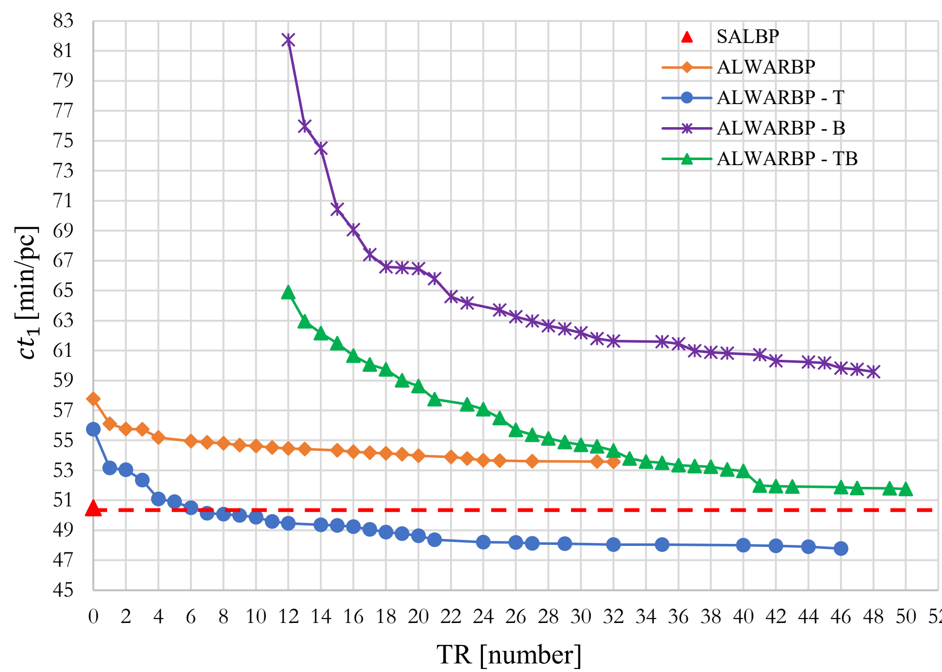
Cases	ALWARBP			ALWARBP-T			ALWARBP-B			ALWARBP-TB		
	TR	ct_1[min/pc]	CPU/s	TR	ct_1[min/pc]	CPU/s	TR	ct_1[min/pc]	CPU/s	TR	ct_1[min/pc]	CPU/s
Case 1	1	1.97	0.10	1	1.81	0.19	16	4.57	1.33	16	3.69	0.35
	24	1.83	0.31	6	1.78	0.54	23	3.14	1.12	19	2.87	0.46
Case 2	1	56.10	0.84	1	53.17	1.65	12	81.73	1.99	12	64.90	3.71
	32	53.57	106	46	47.78	3015	47	59.58	37.48	50	51.77	668
Case 3	1	123.2	0.42	1	115.62	6.2	24	170.58	11.45	24	140.95	23.31
	75	116.5	2504	62	102.70	15115	58	127.83	344.5	58	111.4	3103

Model application in medium case



Case	2
Problem characteristics	Medium
Number of tasks	80
Number of task precedencies	93
CT of the initial design (SALBP) [min]	50.50
Number of workstations and assemblers	6
Number of experienced assemblers	-
Number of low experienced assemblers	3
Number of inexperienced assemblers	3
Number of trainers	2

Scenarios	Task time	Physical workload	Trainer's contribution	Rest Allowance (RA)
ALWARBP	×			
ALWARBP-T	×		×	
ALWARBP-B	×	×		
ALWARBP-TB	×	×	×	



Model application in medium case

$$\left(1 + RA_j\right) \sum_i \sum_w t_{iw} \, x_{ijw} \le ct_1 \;\forall\, j = 1,..,J^*$$

$$RA_j = max \left\{ 0 \, ; \, \frac{\frac{\sum_i \sum_w x_{ijw} \;\, e_i}{\sum_i \sum_w x_{ijw} \;\, t_{iw}} - MAEE_w}{MAEE_w - ET_R} \right\} \forall\, j = 1,..,J^*$$

MAEE = 0.0016 [(60-0.55 AGE) BW eSilva et al. (2016)

RA_j	**Rest Allowance**
e_i	**Energy required to process task *i***
$MAEE_w$	**Maximum Acceptable Energy Expenditure for assembler *w***
ET_R	**Rest Energy-Time ratio (1.86 kcal/min)**

Scenarios	Task time	Physical workload	Trainer's contribution	Rest Allowance (RA)
ALWARBP	×			
ALWARBP-B	×	×		
ALWARBP-RA	×			×