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Walking Workers systems: a sequence analysis for flexible mixed model lines

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Abstract: The Walking Workers (WW) systems are interesting for their flexibility attributes, especially in terms of ability to manage the product variety and market demand. This paper aims to study the mixed model sequencing problem considering un-paced, unbuffered WW systems. The authors propose an original algorithm, called "accordion algorithm" for the models sequence definition and the makespan minimization. This algorithm is tested and validated through a simulative study highlighting the influence of the task time variations and of the resources number on the system performances.

Keywords: Walking Worker, Sequencing, Mixed Model Lines

1. INTRODUCTION

To compete in today's market, companies need to offer a wide range of products (Faccio et al., 2015). The increasing personalization of product variety, the market demand peaks as well as the reduction of product life cycle impose the revision of the production systems from a flexibility perspective (Azzi et al., 2012a). A significant effort is related to flexible and reconfigurable production processes and systems (Atiya et al., 2010). The flexibility requirements related to the manufacturing systems can be summarized as follows: mix flexibility, i.e., the ability to manage a wide mix of components and products, volume flexibility, i.e., the ability to manage the market demand fluctuations with a make to order strategy, layout flexibility, i.e., the ability to change the production resources disposition, number, and assigned tasks (Barbazza et al., 2017). Due to the high requirement of flexibility, manual production is the most used assembly technology in the modern manufacturing systems. Manual operations are used in complex tasks, especially when the products variants force the handling of thousands of parts and when the use of specialized machines and equipment is unjustifiably expensive.

A conventional manual production line is characterized by the presence of one (or more) fixed worker (FW) in each workstation. When the operation is completed the product is moved to the following worker/workstation (Wang, at al., 2005). This type of production line is called a fixed worker line. The volume flexibility and the mix flexibility can require adjusting the tasks assignment, the related location of tools, equipment and parts to assemble and the number of workers and workstations. From this perspective, even if FW system can reach a good level of mix flexibility (Azzi et al., 2012b), it presents low levels of volume and layout flexibility. An alternative approach is the so-called walking worker (WW) production system, where the worker travels along the line carrying out all the tasks in all workstations (Cevikcan, 2016). Typically, the number of walking operators is minor than the number of workstations (Figure 1), while, if equal, the FW configuration is preferred.

Fig. 1. Example of WW system with 5 stations and 3 operators in a U shape configuration.

WW are cross trained so that each one of them fully assemble the product from the beginning to its end. Nakade and Ohno (2003) demonstrated how the application of WW systems can achieve easier line balancing, to reduce the number of buffers required, to reach greater variations in the work time and a better adjustable number of line workers as function of the demand requirements. For these reasons it is adopted in mixed model systems where great variations of production time is present as consequence of production mix and volume variations. From the system point of view the WW, as well as FW, can be designed as a straight-shape line or as a U-shape line, as a paced synchronous or un-paced asynchronous system, with or without buffers between the stations (Boysen et al., 2007).

Un-paced, un-buffered WW production systems can be considered interesting for its capacity of eliminating the waste deriving from the work in progress (WIP) and of balancing the workload variations during the production cycles thanks to the minor number of operators compared to the number of workstations. From this perspective, a potential element of

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optimisation in such production system is represented by the product models sequence that moves from the first station to the last in a FIFO (first input-first output) way.

In the literature, the problem of determining production sequence of models assembled on the line, by optimising a certain performance is called mixed-model sequencing (MMS). On the other hand, considering a WW system the MMS problem has been not properly studied, even if its dynamic characteristics can offer a concrete possibility of performance increasing, especially (but not only) in terms of productivity.

The main contribution of the paper is to study the MMS in a production field that is widely adopted in industry (floating workers) but not study in theory. It modelizes this problem considering the specific attributes of the studied system. Secondly, through a simulative study, highlight the strong dependence of the system productivity versus the adopted models' sequence. Finally, it proposes and validates a heuristic algorithm for the models sequencing, with the aim of minimizing the production make span maximizing the productivity, considering different sets of production mixes, workstation production times and number of WW.

The remainder of this paper is organized as follows. Section 2 presents a brief literature review on MMS and on WW. Then, section 3 introduces the definition and the modelisation of the problem, including the proposed heuristic algorithm. Section 4 reports the simulative study and the proposed algorithm validation, while section 5 reports the conclusions and the further research.

2. LITERATURE REVIEW

Only in the last decades and from the mid-2000 is possible to find the first studies on the WW production systems (Wang et al., 2005). The actual literature is again quite poor of scientific contributions on such production system, especially if compared to their great adoption in industry. The WW systems present some variants.

- The "Rabbit Chase", that is the most common, where typically each worker travels the entire line, moving from one location to another, together with the product to be assembled to perform all the required tasks (Bin Che Ani et al., 2013).
- The "Bucket Brigades", where each worker carries out the work on one piece from one station to another until another worker resumes his work; then, this worker returns to take the job from his predecessor (Bartholdi and Eisenstein, 2005).
- The "Baton Touch", where the products to be assembled are processed one at a time, by multi-functional operators who walk among the various positions assigned to them. Usually each operator must manage multiple stations, not necessarily consecutive (Azzam et al., 2011).

Considering the MMS production lines, different sequencing approaches are available (Boysen et al., 2009).

- MMS to avoid/minimise sequence-dependent work-overloads based on detailed scheduling.
- Sequencing strategies to minimise the sequence-dependent work-overloads by formulating a set of rules-of-thumb, avoiding onerous data collection.
- Level scheduling to find sequences matching the just-in-time (JIT) philosophy about the wear and tear of parts or the minimisation of the product rate variation.

Many contributions are available for MMS in the traditional production with fixed workers (FW). Some authors proposed the use of utility workers (also called "jolly") as a strategy to manage work overload in a production cycle in FW mixed model production lines. This worker takes over to exclusively execute work, whereas the regular worker omits the respective cycle and starts processing the successive workpiece as soon as possible (Faccio et al, 2016). Other contributions are available for FW systems, but it seems that no relevant contributions for MMS are available for WW systems, especially for unpacked unbuffered lines. Recently Hashemi-Petroodi et al. (2020) investigated the impact of dynamic task assignment on the design of a paced mixed-model production line with WW. They demonstrated how this dynamic assignment leads to an increasing of the productivity of each worker. Sedding (2020) proposed a model with the objective to sequence the given jobs on a single machine and to minimize the makespan, considering the worker's operations such that the time-dependent walking times.

Looking at the state of the art, the lack of similar contributes considering WW systems in the literature, as well as the lack of original methodologies to optimise the model's sequences for the make span reduction, demonstrate the interest in investigating this research field.

3. WW SEQUENCING MODEL

The un-paced WW production system is a complex dynamical production environment where different variables concur to the system performance. For a giving production line design, it is possible to consider:

- The number of the WW. The number of WW can change as consequence of the production volume to satisfy.
- The models sequence to produce. In a mixed model line, the production times in each workstation can differ from a model to another because of the specific product options that can be included or not.

Because of these elements, it is possible to study, for a given set of products to assemble, a proper models sequence in order to maximize the system productivity.

3.1 Assumptions

Any MMS problem will at least consist of three basic elements: operational characteristics of the stations, characteristics of the line as a whole and objective to be optimized (Boysen et al. 2009). About the production line the operational characteristics of the stations:

- The production system is an un-paced unbuffered WW production line. These attributes permit to obtain advantages, like the reduction of the occupied space, the reduction of the WIP, the reduction of the throughput lead time. On the other hand, a product will stay in a certain station for the related production time, or more, if an instantaneous bottleneck is created downstream by another model with longer production time. In this last situation an interference occurs between two (or more)

WW, with consequential waiting and idle time of the upstream operator(s).

- The stations are arranged in a serial manner along the flow of the line and the number of stations derived by the balancing inside the proposed procedure. The WW system layout could be different (i.e., straight, U shape, etc.). The balancing solution does not consider increment of stations (and of the related regular workers) to manage the work overload times.
- The model mix, i.e. the demand for models throughout the planning horizon (usually a shift or a day), and all processing times per model and station are known with certainty.
- Consecutive units are placed on the line as soon as a WW is available to start assembling.
- There is a certain number of WW within the line, from a minimum of one to a maximum equal to the number of workstations.
- A WW moves from a station to the next one following the same production flow direction, without the possibility to overcome the next downstream operator. Moreover, he/she assembles the same product in the different stations passing them all from the first to the last. After, if other product models still must be assembled, the operator will move to the first station starting the production of the next model considering the models' sequence.
- The travelling time of the operators from a station to the next one is considered not relevant versus the production times.

The objective of the proposed MMS problem, for a given number of WW and production stations, is the productivity maximisation, i.e., the minimisation of the total production time for the given set of models to assemble. Because of the MMS problem is NP-hard (Moradi and Zandieh, 2013) and because of the dynamical attributes of the presented WW system, this paper proposes a heuristic algorithm that, for a giving set of models to assemble, aims to minimize the number of instantaneous interferences between upstream and downstream operators during the production cycles. The algorithm performances are analysed through simulation with a comparison against other sequencing approaches.

3.2 Notations

The following notations are introduced:

M number of models, (index *m*)

K number of stations, (index *k*)

W number of WW (index *w*), with $1 \leq W \leq K$

d_m short-term demand for model *m* during the planning period [pieces/time]

$D = \sum_{m=1}^{M} d_m$, total demand for the short-term demand mix, (1)

t_{mk} processing time per unit of model m at station k

t_m total processing time per unit of model m, with

$t_m = \sum_{k=1}^{K} t_{mk}$ (2)

$t_{tot} = \sum_{m=1}^{M} t_m$ total processing time (3)

$Max\_t_m = max_k\{t_{mk}\}$ max processing time for model *m* (4)

R^{max} maximum number of possible rounds for the WW during the production of *D*, with

$R^{max} = \left\lceil \frac{D}{W} \right\rceil$ (5)

R^{mim} minimum number of possible rounds for the WW during the production of *D*, with

$R^{min} = \left\lfloor \frac{D}{W} \right\rfloor$ (6)

r_w production line rounds *r* for WW *w* for producing *D*, with $R^{min} \leq r_w \leq R^{max}$, with

$r_w = \left\lceil \frac{D-(\sum_{j=0}^{w-1} r_j)}{W-(w-1)} \right\rceil$, with for $j=0$, $r_0 = 0$ (7)

i round index with $i=1,\dots,R^{max}$

r_{wi} round *i* of the r_w for the WW *w, i.e., the index of the line round for the operator* w

W^{LR} operator who performs the last line round

$W^{LR} = D - R^{min} \cdot W$ (8)

3.3 The "accordion" sequencing algorithm

Because of the basic element of productivity loss in the WW sequencing is represented by the waiting times of fast upstream operators versus one (or more) slow downstream operators, the basic idea of the proposed algorithm is to decouple fast and slow operators during the different rounds. Figure 2 shows the *"accordion"* effect that is possible to create with a proper models sequencing and operators split. As represented in Figure 2, alternating "fast" and "slow" models to assemble between two (sets) operators and during the different line rounds, is possible to obtain the *"accordion"* effect, that permits to reduce or even eliminate the interferences among the operators, especially in the cases where the upstream wait for the production task completion of the downstream ones. Using this effect, the *"accordion"* algorithm is proposed.

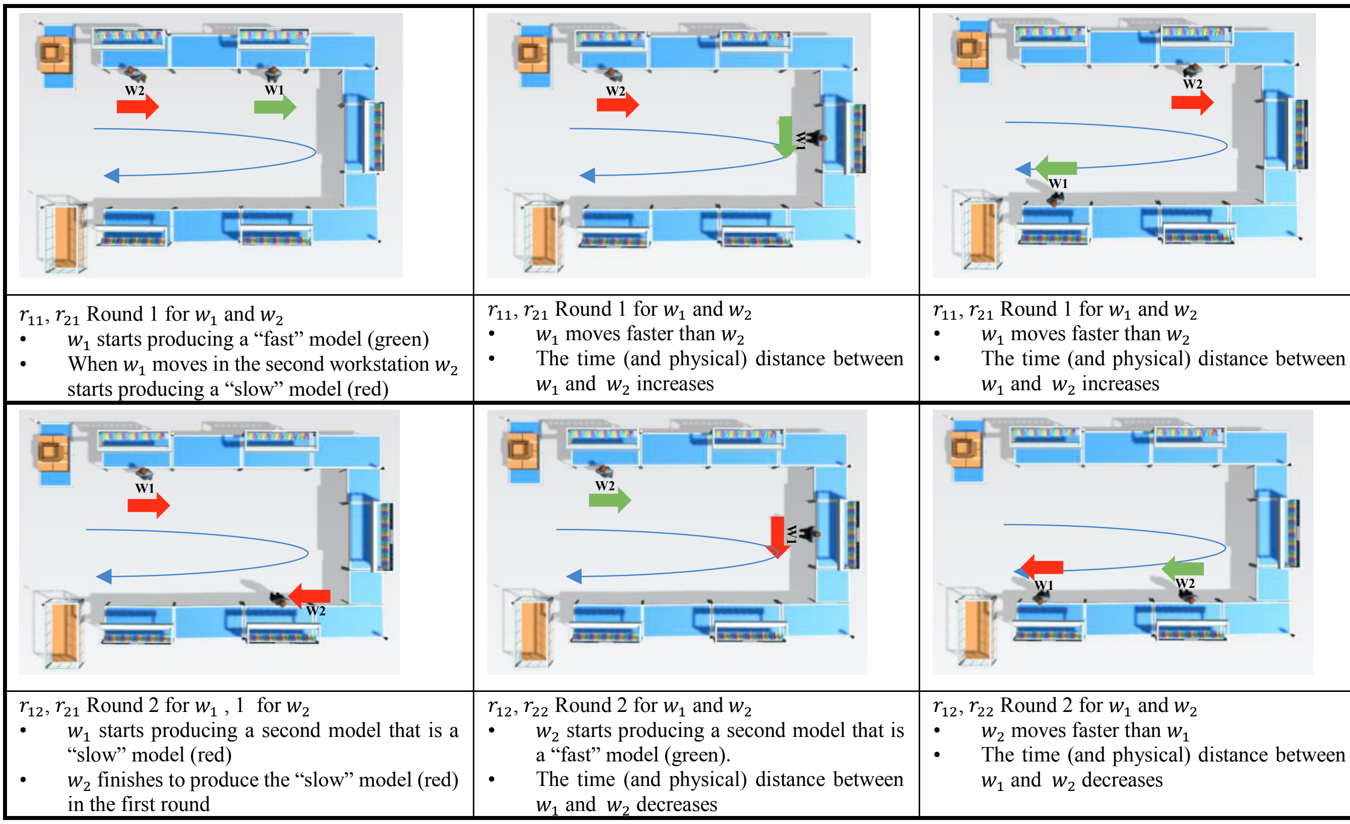

Fig. 2. The "*accordion*" effect, considering for example 2 operators, created with a models proper sequencing and operators split.

Given a production system with K station, a set of M models with a quantity d_m to produce, where the production time for each station k for each model m is t_{mk} the following 3 steps must be developed.

- *Step 1*

In this step the models' vector is created considering the production times and the demand of each model *m*.
1.1 Calculate
$Max\_t_m = Max_k(t_{mk})$
1.2 Create a vector V_p with *p=1,…,D* elements, ordered from minor to major in the index *p* according Max_t_m *of each model m*.
$V_p \coloneqq \{m_d, \dots, m_c\}$, with m_d and m_c generic models.

- *Step 2*

In this step, two sets of operators are created. Each set of operators will alternate during the line rounds "fast" models and "slow", in an opposite way creating the *"accordion"* effect.
Split the WW in 2 sets, with

$$x = \left\lfloor \frac{W}{2} \right\rfloor \tag{9}$$

$S_{1,w} \coloneqq \{1; \dots; x\}$ (x elements)
$S_{2,w} \coloneqq \{x+1; \dots; W\}$ (W-x elements)

- *Step 3*

In this step the models' sequence is finally created considering the line rounds. To explain the step 3 an example is reported considering *W=5, D=12* and **M=10.**

- The ordered V_p is reported in the first column as refined by the step 1 of the procedure.
- $S_{1,w} \coloneqq \{W1, W2\}$ and $S_{2,w} \coloneqq \{W3, W4, W5\}$, as defined by the step 2 of the procedure.

Table 3. Step 3 example

			Walking Workers line rounds					
Vp	Models	Max_t_m	*Round 1*		*Round 2*		*Round 3*	
V1	M1	10	S1: FAST	W1				
V2	M2	12		W2				
V3	M2	12			S2: FAST	W3		
V4	M3	14				W4		
V5	M4	15				W5		
V6	M5	16					S1: FAST	W1
V7	M8	17						W2
V8	M8	17			S1: SLOW	W1		
V9	M6	18				W2		
V10	M7	20	S2: SLOW	W3				
V11	M10	21		W4				
V12	M9	22		W5				

1. In the first Round *S1* walking workers produce the "fast models", while *S2* the "slow models" following the V_p order.
2. In the second round they switch creating the "accordion".
3. In the third round they exchange again. Is interesting to notice that only *W1* and *W2* perform the third round.

The result of the accordion algorithm is the sequence matrix shown in Table 2 where is reported an example of the *"accordion"* algorithm application with D=11 product to assemble, W=4 working workers (divided into 2 sets with 2 operators each).

4. SIMULATION ANALYSIS AND VALIDATION

In this section the proposed algorithm has been analysed through a simulative approach. A discrete event simulation software package has been used, simulating the production system reported in Fig.1. The production system is composed by *K=5* stations that produce *M=5* models, with $d_m = 2, \forall m$.

Table 2. Sequence matrix example, *with D=11, W=4,* $\boldsymbol{R^{max}}$ *=3,* $\boldsymbol{R^{min}}$ *=2,* $\boldsymbol{r_1 = 3, r_2 = 3, r_3 = 3, r_4 = 2}$

	S_1		S_2	
round	w_1	w_2	w_3	w_4
1	V_1	V_2	V_{1o}	V_{11}
2	V_8	V_9	V_3	V_4
3	V_5	V_6	V_7	

The number of WW *W* varies consequently from 1 to 5. To understand the influence of the production times variations on the sequencing algorithm performances, 6 different scenarios have been evaluated with different processing time t_{mk} variation levels. To summarize the variance of the t_{mk} the Coefficient of Variation *CV* is used. The coefficient of variation (CV) is a measure of relative variability and it is the ratio of the standard deviation to the mean (average). In our case

$$\mathrm{CV} = \frac{\sigma_t}{\mu_t} \qquad (10)$$

Where σ_t is the weighted standard deviation of the t_{mk} compared to d_m. μ_t is the weighted mean of the t_{mk} compared to d_m. Table 3 summarizes the 6 scenarios main data.

Table 3. Simulation Scenarios

Scenario	*Models*	*D*	*CV*	*ttot [hh:mm:ss]*
0	5	10	0%	06:40:00
1	5	10	12%	06:40:00
2	5	10	20%	06:40:00
3	5	10	45%	06:40:00
4	5	10	50%	06:40:00
5	5	10	68%	06:40:00

To make the simulation results comparable, for all scenarios, the total production time t_{tot} is the same as well as the average production times for the station $\mu_t = 8$ .The *CV* varies from *0* $(t_{mk} = 8, \forall m, k)$ to 68%.

Table 4. Example of Scenario 3 input data [min/piece]

Model	*St1*	*St2*	*St3*	*St4*	*St5*	*dm*	*tm*	*Maxtm*
A	14	4	14	4	14	2	50	14
B	6	11.5	6	11,5	6	2	41	11.5
C	7	10	7	10	7	2	41	10
D	4	12	4	12	4	2	36	12
E	4	10	4	10	4	2	32	10

Table 4 reports an example of the scenarios data (Scenario 3) with t_{mk}, d_m, $Maxt_m$. Table 5 reports the sequences tested and compared for scenario 3. There are compared, considering the different WW cases from 1 to 5:

- *Random* sequence.
- *LTPT* sequence (largest total processing time).
- *STPT* sequence (shortest total processing time).
- *FIFO* sequence (considering the model name).
- *LIFO* sequence (considering the model name).
- *"Accordion" Algorithm (A.A.)* as described in section 3.3.

Table 5. Example of Scenario 3 sequences

Sequence Method	*WW*	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
A.A.	1	E	A	E	A	C	D	C	D	B	B
A.A.	2	E	A	A	E	C	D	D	C	B	B
A.A.	3	E	A	A	D	E	C	C	B	D	B
A.A.	4	E	E	A	A	D	D	C	C	B	B
A.A.	5	E	E	D	A	A	B	D	C	C	B
LTPT	1-5	A	A	B	B	C	C	D	D	E	E
STPT	1-5	E	E	D	D	C	C	B	B	A	A
FIFO	1-5	A	B	C	D	E	A	B	C	D	E
LIFO	1-5	E	C	D	B	A	E	C	D	B	A

Table 6 shows the simulation result for Scenario 3 in terms of Make Span *(MS)* for producing the *D=10* models of the sequence changing the number of walking worker from 1 to 5.

Table 6. Example of Scenario 3 simulation output

	Make Span [hh:mm:ss]				
WW	1	2	3	4	5
LTPT	06:40:00	03:34:00	02:41:00	02:26:00	02:23:30
STPT	06:40:00	03:34:00	02:41:00	02:26:00	02:23:30
FIFO	06:40:00	03:43:00	02:43:00	02:22:00	02:20:00
LIFO	06:40:00	03:43:00	02:43:00	02:22:00	02:20:00
Random	06:40:00	03:56:00	03:11:00	02:34:00	02:30:00
A.A	06:40:00	03:34:00	02:40:00	02:21:30	02:17:30

To make the make span results comparable, the make span data *MS* have been normalized compared to the common total processing time t_{tot} as MS/t_{tot}. 6 scenarios have been analysed considering 5 different WW situations (from 1 to 5) and 6 different models sequencing methods for 180 different final combinations. In 177 of 180 of the tested scenarios the *A.A.* gives equal or better performances than the other sequencing methods. The results firstly show a strong influence of *CV* and *w* on the Make Span. The increase of *w* as expected, decreases the MS but less than linearity. On the other hand, the increase of CV increases MS the more the number *w* is greater (Fig. 3). Comparing the r*andom versus A.A.* sequences performance it is clear how *A.A.* performs better the more is the CV of the processing times.

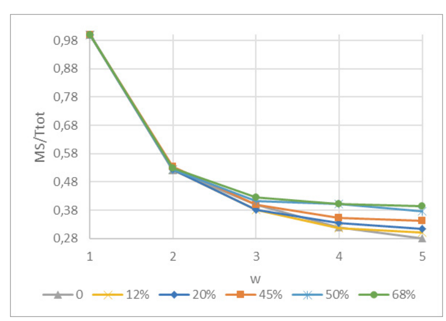

Fig. 3. Performances of the *A.A.* algorithm for the different values of *CV* as function of the number of the of WW.

5. CONCLUSIONS

This paper aims to study the MMS considering un-paced, unbuffered WW systems. The authors the "*accordion algorithm*" for the models' sequence definition for the makespan minimisation. The process times variations for the different models and stations, as well as the number of WW, have an impact of the make span system performance, enforcing the practical implications of the research. This algorithm has been tested and validated through a simulative study where 180 scenarios have been analysed. The results show how the proposed approach performs better than other sequencing rules and random sequences.

The development of performing sequencing algorithms for WW systems is a future field of research.

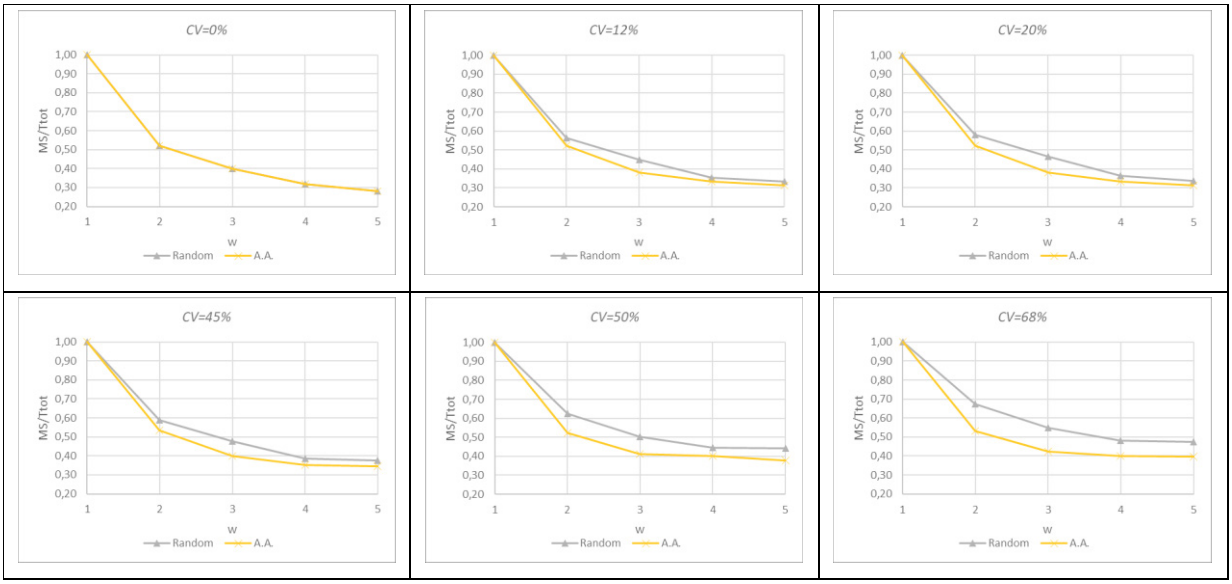

Fig. 4. Random versus A.A. sequences performance comparison for MS/t_{tot} for different values of CV and w.

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