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СТРУКТУРА ПРОГРАММНЫХ КОМПЛЕКСОВ ДЛЯ РАЗРАБОТКИ ЦИФРОВЫХ ДВОЙНИКОВ ОДЕЖДЫ: ПРАВИЛА ФОРМИРОВАНИЯ*

STRUCTURE OF SOFTWARE PROGRAM PIPELINES FOR CREATING DIGITAL CLOTHING TWINS: PRINCIPLES OF DESIGN

А.Ю. МОСКВИН, М.А. МОСКВИНА, В.Е. КУЗЬМИЧЕВ

A.YU. MOSKVIN, M.A. MOSKVINA, V.E. KUZMICHEV

(Saint Petersburg State University of Industrial Technologies and Design, Ivanovo State Polytechnic University)

(Санкт-Петербургский государственный университет промышленных технологий и дизайна, Ивановский государственный политехнический университет)

E-mail: wkd37@list.ru

Digital twins modelling uses pipelines which include sets of software programs as the initial data overcomes on its way to the final digital object. This study presents a new approach to pipelines creation using combinatory and parameterisation. It uses requirement matrix to choose the software programs, combines them in hypothetical pipelines and evaluates the pipelines by means of a new set of parameters. Two women costumes were taken as examples to analyse the combinations of software. A requirement matrix which is based on the requirements for the digital twins and the tools and functionality of 26 contemporary software programs was developed. The matrix was employed to filter out software programs that cannot be used to produce the digital twins under the given sets of criteria. The software programs that meet the requirements were combined to form 10800 hypothetic pipelines. A new set of pipeline parameters, the labor intensity of generating a digital twin, the difficulty of mastering, the price and an integral indicator called resource requirements index (RRI), was introduced. Using new indicators, the four most effective complexes for each digital twin were selected and described: the least labor-intensive, easiest to learn, the cheapest and most balanced.

Для моделирования цифровых двойников используют программные комплексы в виде совокупности компьютерных программ и алгоритма их применения для обработки исходных данных и генерирования конечного цифрового объекта. В этом исследовании представлен новый подход к формированию программных комплексов с использованием принципов комбинаторики

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и параметризации. Сформирована матрица требований для фильтрации компьютерных программ, объединения их в гипотетические комплексы и оценивания результативности с помощью нового набора параметров. Для анализа процесса формирования программных комплексов использованы два женских костюма: современный и театральный. Сформирована матрица, основанная на требованиях к цифровым двойникам и функциональным возможностям и инструментам 26 общедоступных программ. Матрица, оперирующая заданными критериями, может помочь разделить программы на те, которые нецелесообразно использовать для создания цифровых двойников и которые можно использовать. Предложены новые показатели для оценки программного комплекса: трудоемкость генерирования цифрового двойника, сложность освоения, цена и комплексный показатель потребности в перечисленных ресурсах. С помощью новых показателей выбраны и описаны четыре наиболее эффективных комплекса для каждого цифрового двойника: наименее трудоемкий, легкий в освоении, самый дешевый и сбалансированный.

Keywords: digital twin, 3D modelling pipeline, virtual try on, avatar, modelling workflow, digitisation, software.

Ключевые слова: цифровой двойник, программный комплекс, виртуальная примерка, аватар, процесс моделирования, цифровизация, программное обеспечение.

Introduction

Digitisation of apparel industry requires software platforms that accumulate functionality and benefits of cutting-edge computer technologies. The digital twin of clothes is a structural model of a «body-clothes» system supplemented by information links between the model and the system. In this regard, digitisation relies on software programs that are used to produce the twins [1-3]. The process of generating the twin involves many steps, such as creation of initial database, human body modelling, pattern drafting, virtual try on, post processing, texture painting, rendering and quality assessment. Each step focuses on different objects and requires special methods to analyse and transform those into digital form. For this reason, one software program cannot be applied throughout the whole process. The practice shows that IT-engineers and 3D modellers use pipelines. The term «pipeline» describes a pass through a set of software programs that the initial data overcomes on its way to the final digital object. This means that different software programs are applied consistently, one after another, and, thus, form the pipeline.

Published results of research works on digital twins of clothes demonstrate different pipelines in according with functionality of software. Moskvin, Moskvina and Kuzmichev combined AutoCAD, Clo3D and 3dsMaxto reproduce a1840 dress suit [4]. AutoCAD, Autodesk Inventor, Clo3D and 3dsMax were applied for parametric modelling of historical crinolines and mannequins [5, 6]. The same authors employed Substance Designer, Make Human, Clo3D and Blender to generate a digital costume of Salt Man4 [7]. Wijnhoven and Moskvin used Autodesk Inventor, 3dsMax, Unreal Engine 4 and AutoCADin order to replicate and reconstruct archaeological mail armour [8, 9]. Several techniques include virtual clothing generation in terms of polygonal modelling, sculpting, 3D scanning and cloth simulation [10]. Cybulska applied CG software to produce 2D and 3D highly-detailed textiles [11]. A set of 2D pattern drafting systems, computer simulation and texture painting packages was applied to generate digital twins of Chinese archaeological clothes [12-14]. Despite encouraging results in using different pipelines, a versatile and systematic approach to creating those is not yet developed.

Fig. 1 shows the schedule of software programs which can be used for modelling 3D digital twins of clothes. 3D modelling designed from six steps. The first step aims to produce a digital copy of the human body called an avatar. The second step uses 2D computer-aided design (CAD) systems for pattern drafting. The third step employs computer simulations to put the garment on the avatar. The fourth step deals with post processing and creating a flat layout of the 3D surface. During the fifth step the 3D model is painted in accordance with colours and textures of textile materials. The last step is dedicated to generating multimedia materials and presenting the digital twin.

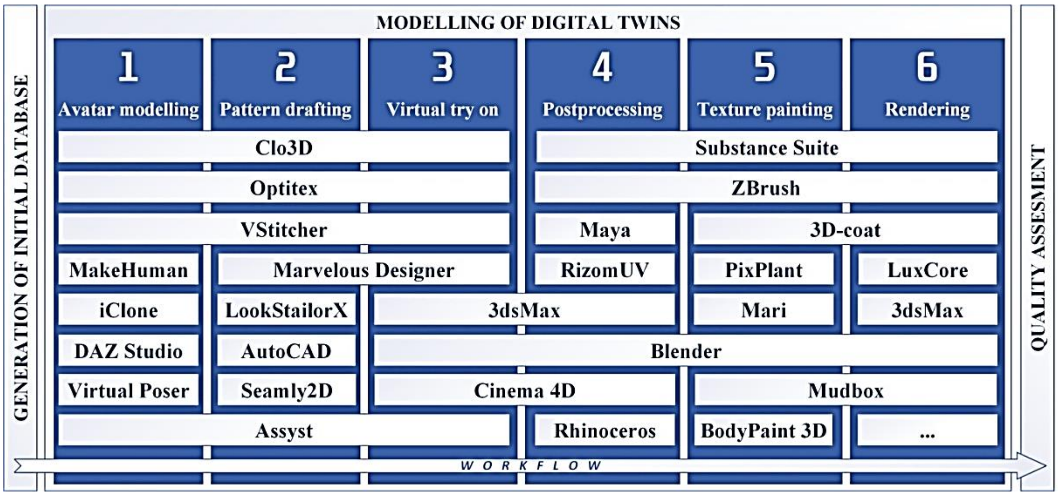

Fig. 1

Most of the programs can be applied only on one of the steps. For example, Make Human and DAZ studio are developed for avatar modelling; Seamly2D and AutoCAD are used for pattern drafting. Several software packages, such as Marvelous Designer, Clo3D, Optitex and Blender, are more versatile and can cover two or more steps of 3D modelling. As can be seen in Fig.1, eight options for software decisions are available on each step. In accordance with the principles of combinatory, 262.144 hypothetic pipelines can be organisedfrom the above-mentioned software programs. The pipelines are not the same. Each of them requires resources, namely, time, staff and money. The resulted «body-clothes» systems differ from each other as well. The features of the garments can be described by using special criteria. In order to meet those, the software program should be able to reproduce all the objects, such as the avatar, the pattern, the textile materials and the 3D structure of the surface of the garment.

This article aims to analyse important aspects of designing pipelines for modelling digital twins and to form a new approach to pipelines creation using the principles of combinatory and parameterisation.

Methods

The study included five stages in terms of a case study. Firstly, two costumes were chosen to analyse the above-mentioned software. Secondly, a requirement matrix for both digital twins was developed. The matrix was used to filter out software programs that cannot be used to produce the digital twins under the given sets of criteria. The software programs that meet the requirements were combined to form hypothetic pipelines. Thirdly, three parameters, namely the laboriousness, the complexity of learning and the price were calculated for each of the pipelines. Fourthly, the three parameters were combined into an integral indicator called resource requirements index (RRI).Fifthly, four most effective pipelines were chosen for generating each twin.

Thus, the study uses four factors to describe the pipelines and compare them against each other. The factors are as follows:

1. Number of operations that should be done. Pipelines with many operations require a lot of time and vice versa.

2. Number of software programs. The number implicitly reflects the time that the engineer invests into mastering the interface and tools of the software.

3. The amount of money required to purchase the software programs.

4. RRI is a combination of the three above mentioned parameters which allows the most balanced pipeline to be revealed.

The less resources for creating the pipeline, the better. Therefore, the values of each of the factors are inversely proportional with the suitability of the pipeline.

Fig. 2 shows photographs of two sets of clothing which were chosen for digitisation: the first one is a contemporary women's suit [15]; the second one is a theatrical costume for the play «A Profitable Position» (1856) by A.N. Ostrovsky. Both digital twins are available at Sketchfab ([16]-[17]). The initial databases for both costumes included body measurements and patterns, as well as theproperties and scans oftextile materials.

Fig. 2

The aims of each step of digitisation are presented in Table 1.

Table 1

Step	Final aim	
	Digital twin 1 of contemporary women’s suit	Digital twin 2 of theatrical costume
1. Avatar modelling	Concordance to traditional body measurements measured in static	Concordance to body measurements after its transformation under corseting effects
2. Pattern drafting	Digitisation of a raster image of the sewing pattern	Standard pattern drafting in CAD software
3. Virtual try on	Reproduction of the 3D shape of the garment using digital textile materials and computer simulations	
4. Post processing	Generating a flat layout of the 3D surface using UV-mapping technology	
5. Texture painting	Standard non-destructive texturing of the surface of the 3D model	Reproduction of historical textiles and signs of wear, such as dirt, scuffs and wrinkles
6. Rendering	Generating 2D image of digital twin	

As can be seen in Table 1, the aims of steps 1, 2 and 5 for the two costumes are not the same. The avatar (step 1) for the first twin represents standard contemporary body size while the second avatar require body shape modifications in accordance with historical corseting effects. The block pattern (step 2) of the first costume is presented as a raster image. Thus, the modelling of the first twin relies on image tracing technology for pattern drafting. The second costume has many decorative elements made from different textile materials which are widely used for theatrical costumes production and require advanced texture painting tools (step 5).

Table 2 shows the requirement matrix which contains criteria for choosing of software programs. The matrix was used to trace the requirements to the digital twins and correlate them with tools and functionality of 26 software programs. The requirements are divided between six groups (Fig. 1). Italic font indicatesspecific criteria relevant only for one of the twins.

Bold font in Table 2 indicates 19 software programs that meet the requirements.

The number of operations and prices for each software program were calculated from official user’s manuals, online video guides, official websites and our personal experience (Fig. 3). The data was processed by using common tools of Microsoft Excel. An operation was considered a sequence of actions with one object, such as a part of the garment or a single texture map. The cost of software was calculated for one month. The information about pricing provided in Fig. 3 is for information purposes only and does not constitute an offer. Up-to-date licensing models and prices are available at the official websites of the developers of the software.

Table 2

Requirements		Software functionality*																									
№	Criteria	**Clo3D**	**Optitex**	**VStitcher**	**MakeHuman**	**iClone**	**DazStudio**	**VirtualPoser**	**Assyst**	**MarvelousDesigner**	**LookStailorX**	**AutoCAD**	**Seamly2D**	**3dsMax**	**Blender**	**Cinema4D**	**Substance Painter**	**ZBrush**	**Maya**	**RizomUV**	**Rhinoceros**	**3D-coat**	**PixPaint**	**Mari**	**Mudbox**	**BodyPaint3D**	**LuxCore**
Step1 – Avatar modelling																											
1.1	Full body avatar with limbs	✓	✓	✓	✓	✓	✓	✓	✓	✓																	
1.2	Rigged 3D model with bones	✓	✓	✓	✓	✓	✓	✓	✓	✓																	
1.3	FBX/OBJ export	✓	✓	✓	✓	✓	✓	✓	✓	✓																	
1.4	Body measurements compatibility	✓	✓	✓	✓				✓		✓																
1.5	*Advanced shape controls***				✓				✓																		
	Result (Digital twin 1)	✓	✓	✓	✓				✓																		
	Result (Digital twin 2)				✓				✓																		
Step2 – Pattern drafting																											
2.1	Non-parametric 2D drawing	✓	✓	✓					✓	✓	✓	✓		✓	✓	✓			✓		✓						
2.2	2D accuracy of 0,1 mm	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			✓		✓						
2.3	Advanced 2D drafting tools	✓	✓	✓					✓			✓	✓														
2.4	*Automated image tracing****											✓															
	Result (Digital twin 1)											✓															
	Result (Digital twin 2)	✓	✓	✓					✓			✓															
Step3 – Virtual try on																											
3.1	Cloth simulation technology	✓	✓	✓					✓	✓				✓	✓	✓			✓								
3.2	Textiles properties compatibility	✓	✓	✓					✓	✓																	
	Result (Digital twin 1 and 2)	✓	✓	✓					✓	✓																	
Step4 – Postprocessing																											
4.1	UV-mapping technology	✓								✓				✓	✓	✓	✓	✓	✓	✓	✓						
4.2	Automated island packing													✓	✓	✓			✓	✓	✓						
	Result (Digital twin 1 and 2)													✓	✓	✓			✓	✓	✓						
Step5 – Texture painting																											
5.1	Real-time texture painting														✓		✓	✓				✓	✓	✓	✓	✓	
5.2	Non-destructive texturing														✓		✓					✓		✓	✓	✓	
5.3	*Automated wear marks*****														✓		✓							✓			
	Result (Digital twin 1)														✓		✓					✓		✓	✓	✓	
	Result (Digital twin 2)														✓		✓							✓			
Step6 – Rendering																											
6.1	PBR rendering technology	✓		✓		✓	✓	✓	✓					✓	✓	✓	✓		✓		✓	✓		✓	✓	✓	✓
6.2	Advanced lighting tools													✓	✓	✓			✓		✓						✓
	Result (Digital twin 1 and 2)													✓	✓	✓			✓		✓						✓

*The result is positive if all the requirements within the group are fulfilled.
**Those include tools required for reproducing corseting effects in digital twin 2.
***Image tracing is used for digitization of the sloper pattern in digital twin 1.
****The signs of wear are reproduced in digital twin 2.

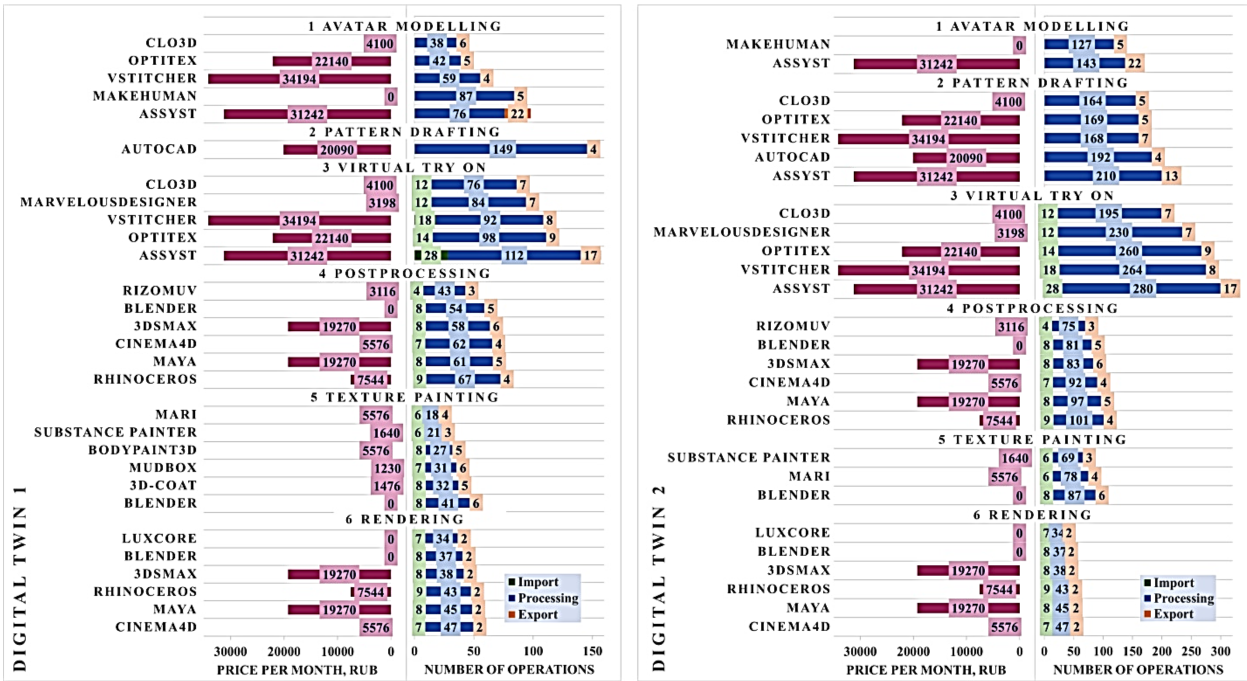

Fig. 3

As can be seen in Fig. 3, the software programs vary in prices and number of operations involved.

Three types of operations exist, i.e. data import, data processing and results export. Thus, the first parameter of the pipeline, namely, the total number of operations *N*, can be calculated by (1)

$$N = \sum_{i=1}^{6} n_i + \sum_{j=1}^{k} m_j\ ; \quad 1 \geq k \geq 5, \quad (1)$$

where n_i is the total number of 3D modelling operations within step *i*; m_j is the total number of operations within export/import procedure *j* required for transferring data from one software program to another; *k* is the number of export/import procedures. *N* describes the time costs of the pipeline and thus can be used to compare the hypothetic pipelines and chose the most effective once.

In accordance with International Computer Driving Licence (ICDL) [18, 19], three levels of proficiency in digital skills exist - base, standard and advanced - which reflect an inter alia, a time on task (also known as task completion time) [20]. The user spends a time on each operation. As digital skills are increasing, the time on task is decreasing. Thus, the beginners spend more time on each operations than more experienced users. That aspect can be taken into account by using a correction coefficient of time on task that reflects the ratio for particular user to average user. The coefficient can be calculated from learning curves [21], which describe the mathematical dependency existing between the time invested into learning and the progress achieved. For example, the formulas by L.L. Thurstone [22] can be applied to calculate above-mentioned correction coefficient for the complex learning curve, S-curve, diminishing returns curve and increasing returns curve [23, 24].

The second parameter-the number of software programs within the pipeline *P* -is calculated by using (Eq. 2)

$$P = \sum_{i=1}^{6} p_i, \quad (2)$$

where p_i is the number of software programs at step *i*.

The third parameter – the price of the pipeline *S* – can be evaluated by (Eq. 3)

$$S = \sum_{a=1}^{P} s_a, \quad (3)$$

where s_a is the price of the software program and *P* is the number of programs within the pipeline.

The resource requirements index *RRI*, which summarizes the values of *N*, *P* and *S*, was calculated by means of three values. The average values $N_{average}$, $P_{average}$ and $S_{average}$ were calculated as arithmetic means for all the hypothetic pipelines.The values of N_{actual}, P_{actual} and S_{actual} (1-3) for each pipeline were divided by $N_{average}$, $P_{average}$ and $S_{average}$to calculate the relative values$N_{relative}$, $P_{relative}$ and $S_{relative}$ by (Eq. 4)

$$RRI = \begin{pmatrix} N_{relative}W_N + P_{relative}W_P + \\ +S_{relative}W_S \end{pmatrix} \cdot 100; (4)$$

$$0 \geq W_N \geq 1;\ 0 \geq W_P \geq 1;\ 0 \geq$$
$$\geq W_S \geq 1;\ W_N + W_P + W_S = 1$$

where W_N, W_P and W_S is the weight of *N*, *P* and *S* which reflects the importance of the parameters in relation to individual or official factors. To simplify all the calculations, the parameters in this case-study were considered equally important.The weight of each parameter was equivalent to 0,33.

RRI equal to 100 indicates average requirement in resources. RRI less than 100 shows that the pipeline requires less resources than the average one. RRI more than 100 indicates resource-intensive pipelines.

Results and discussion

Fig. 4 shows a scheme of 5400 hypothetic pipelines for each of thedigital twins. Each software program meets the criteria listed in the requirement matrix (Table 2).

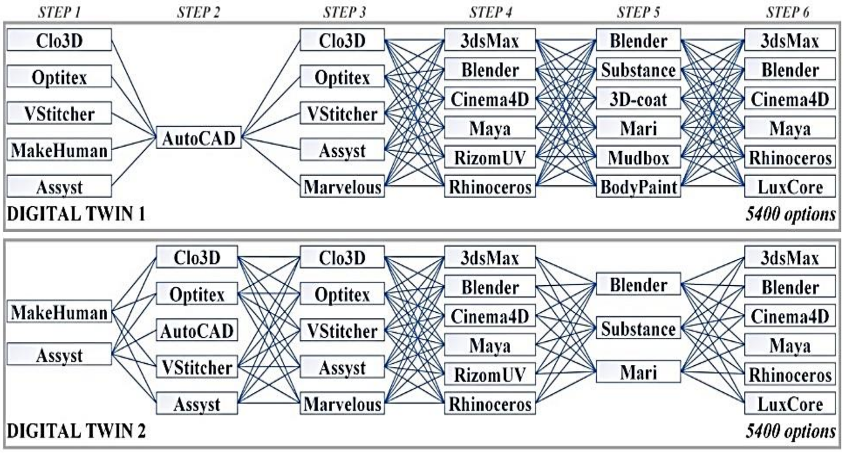

Fig. 4

Table 3 shows the parameters, N, P, S and RRI, which were calculated by using (1-4).

Table 3

Digital twin	Number of hypothetic pipelines	*N*			*P*			S, RUB/month			RRI		
		min	average	max	min	average	max	min	average	max	min	average	max
1	5400	413	501	599	3	6	6	23288	70981	117916	59,7	100	127,2
2	5400	709	846	984	2	5	6	4100	64728	119964	50,4	100	133,6

Table 3 shows that hypothetic pipelines vary in complexity and characteristics. The number of operations ranges from 413 to 599 and from 709 to 984 for twins 1 and 2. The number of software programs varies from two to six. The price of the pipelines is between 4100 and 119964 RUB. *RRI*, which ranges from 50 to 133, indicates that the process of digital twin modelling uses different amount of resources depending on the chosen pipeline.

In order to filter out the pipelines and chose the relevant ones, the values of N_{actual}, P_{actual} and S_{actual}, the relative values $N_{relative}$, $P_{relative}$ and $S_{relative}$ and *RRI* were calculated for each of 10800 pipelines. The calculated values were used to choosemost effective pipelines for each twin: for twin 1 – 1.1, 1.2, 1.3 and 1.4; for twin 2 - 2.1, 2.2, 2.3 and 2.4 (Table 4).

Table 4

No.	Features	N		P		S, RUR/month		RRI
		N_{actual}	$N_{relative}$	P_{actual}	$P_{relative}$	S_{actual}	$S_{relative}$	
Digital twin 1								
1.1	The least laborious	413	0,82	5	0,88	32882	0,46	72
1.2	The cheapest	484	0,97	5	0,88	23288	0,33	88
1.3	Easy to master	490	0,98	3	0,53	42230	0,59	70
1.4	Balanced	461	0,92	3	0,53	24190	0,34	59
Digital twin 2								
2.1	The least laborious	709	0,84	5	0,92	8856	0,14	63
2.2	The cheapest	744	0,88	4	0,74	4100	0,06	56
2.3	Easy to master	955	1,13	2	0,37	31240	0,48	66
2.4	Balanced	757	0,89	3	0,55	4100	0,06	50

Fig. 5 shows graphical representations of resulted pipelines.

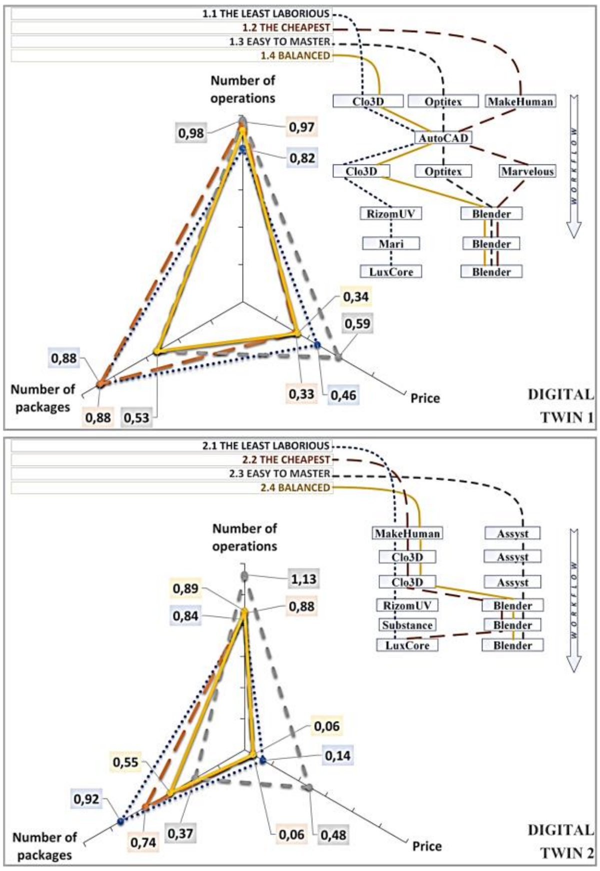

Fig. 5

The radar charts show the balance between three relative parameters in each pipeline.

Pipelines 1.1 and 2.1 has the lowest *N* and require minimum operations. Pipelines 1.2 and 2.2 has the lowest *S*and the lowest prices. Thus, those pipelines are available for small organisations and individual modellers. Pipelines 1.3 and 2.3 has the lowest P. They include 2-3 software packages which makes mastering the interface and tools of the software less time consuming. Pipelines 1.4 and 2.4 has the lowest *RRI* values. They are the most balanced ones and present compromises between the lowest values of *N*, *S* and *P* values.

As can be seen in Fig.5, the case-study resulted in the algorithm of a new method which allows to reduce the number of hypothetic pipelines from 5400 to 4. Thus, the presented approach allows individuals and organisations to create pipelines that meet their preferences, demands and possibilities. Moreover, new parameters *N*, *P*, *S* and *RRI* design a new parametric approach to digital twins modelling.

CONCLUSIONS

The article reveals important aspects of compiling pipelines for digital twins modelling and provide new algorithm to pipelines creation. The results of the study can be summarised as follows.

1. A new approach to pipelines creation using combinatory and parameterisation was developed. It is based on a new set of software programs parameters, combining them in hypothetical pipelines, a matrix to filter them out and equations to evaluate the pipelines.

2. A requirement matrix for tracing the requirements to digital twins and correlating them with functionality of 26 contemporary software programs was developed. The matrix was employed to filter out software programs that cannot be used and choose appropriate programs to form hypothetic pipelines and produce the digital twins under the given sets of criteria.

3. A new set of pipeline parameters including numbers of operations and software programs, the price and an integral indicator called resource requirements index (RRI) was introduced. The new parameters were employed to choose and describe four most effective pipelines, i.e., the least laborious, the cheapest, «easy to master» and «balanced».

The presented approach has several limitations.

1. The number of operations should be combined with «*average time on task*» to describe the time costs more precisely.

2. Experienced engineers use custom combinations of software programsand refrain from altering those if they are able.

3. Clo3D, Assyst and Vstitcher provide users with more accurate tools for computer simulations and, thus, increase the accuracy of digital twins. Thus, the quality of results should be considered along the set of pipeline parameters presented in this article.

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