Supplementary Material for Resource Choreography in Cyber-Physical-Social Systems: Representation, Modeling and Execution

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1 Experiment Setup

Table 1 lists the resources including their descriptions, services and events.

Since the informatization of the real world has not reached a satisfactory level, the software-defined manner of different resources is still a big challenge. Therefore, in order to ensure the feasibility of the execution architecture, we design a set of software-defined manners for the resources from different spaces.

- *(M1)*. Interface exposure by *Robot Process Automation (RPA)* [1] or *Deeplink* [2]. It indicates to identify and encapsulate the software interface of an application at the software level. This manner can be applied to the cyber resources and physical resources. These resources are usually cloud services or mobile applications (including the applications to control the physical devices) that have been developed. Generally the applications are closed which means they do not provide external interfaces. In this case, we can apply the technique of *RPA* or *Deeplink* to expose the service interfaces of an application.
- *(M2)*. Unified interface by device management platforms. This manner is mainly used for physical resources that the physical devices are connected to the management platform providing the unified service interfaces. $HomeAssistant$ [3] is a well-known device management platform which supports the software-defined manner.
- *(M3)*. Collaborative manipulation and perception by other actuators or sensors. The former means that an actuator which has been defined by software is used to control another device which cannot be controlled by software. For example using a software-defied robot to manipulate the traditional household appliances. The latter manner is used to publish the events of the resources when the resources do not have the ability to publish events autonomously. This manner is suitable for the physical resources and social resources. For example, an image sensor can be used to perceive the indicator light of a water dispenser to determine whether the water is boiled.
- *(M4)*. Manual assistance by volunteers. It means that the service execution of the resource is driven manually, or the event of the resource is observed and published manually. It is a supplement to the software-defined method, addressing the difficulty that services or events cannot be defined at the software level. This manner is usually applied to the cyber resources and physical resources. For example, the event of finishing making coffee can be reported by a volunteer beside the coffee maker. Subsequently, the report was officially published at the software level through software callback.
- *(M5)*. Crowdsourcing platform. This manner is a typical way of gathering human resources. Usually workers who join the crowdsourcing platform can take on tasks and inform the platform the completion of tasks. This corresponds to a special type of software-defined social resource. A crowdsourcing platform is generally implemented as a mobile application which volunteers can install and register.

The resources in the experiment environment are software defined in different manners. As is shown in Table 1, cyber resources such as Dingding and Taobao are defined using *M1*. For example, we use the RPA approach to record the operation process of Dingding in the form of scripts and encapsulate them in a RESTful interface. When the $PunchIn$ service is requested, the $PunchIn$ script will be executed. When the execution of script ends, the $FinishPunchingIn$ event is triggered.

Physical resources are defined using *M1*, *M2*, *M3* or *M4*. Some physical resources such as the weighing scale and the air purifier have corresponding mobile Apps. Among them, the weighing scale is defined using *M1*. The air purifier can be directly connected to the $HomeAssistant$ platform, thus is defined using *M2*. In addition, we apply *M4* to defined the traditional air conditioner. In this case, a volunteer is invited to operate the control panel installed on the wall and observe the values on the panel. Furthermore, we use *M3* to

TABLE 1
Resource List

Type	Name	Description	Service	Event
Cyber Resource	Taobao	An app for shopping	MakeOrder(M1)	OrderCompleted(M1)
	Keep	An app that can play fitness videos	PlayVideo(M1)	FinishPlaying(M1)
	Starbucks	An app that for ordering coffee	PlaceCoffeeOrder(M1)	OrderCompleted(M1)
	Dingding	An app for punch-in subscriptions	PunchIn(M1)	FinishPunchingIn(M1)
	Wechat	An app for chatting	SendMessage(M1)	MessageReceived(M1)
	SMS	A system app for sending and receiving text messages	SendMessage(M1)	MessageSent(M1)
			—	MessageReceived(M1)
	MeetingServiceSystem	A self-developed cyber system for conference rooms	InitiateMeetings(M1)	Notification(M1)
			FillingAppointments(M1)	AppointmentCompleted(M1)
			—	Notification(M1)
			UploadDocument(M1)	FinishUploading(M1)
	Orders	A self-developed cyber system for submitting orders	MakeOrder(M1)	OrderCompleted(M1)
Physical Resource	Printer	A device for printing documents	PrintFile(M2)	FinishPrintingFile(M2)
	CoffeeMachine	A device for brewing coffee	MakeCoffee(M2)	FinishMakingCoffee(M4)
	Camera	A device for detecting humans	—	HumanDetection(M2)
	WeighingScale	A device for weighing	GetWeightData(M1)	WeightUpdated(M1)
	AirCleaner	A device for air purification	TurnOnAirCleaner(M2)	AirCleanerTurnedOn(M2)
			TurnOffAirCleaner(M2)	AirCleanerTurnedOff(M2)
	AirConditioner	A device for regulating laboratory temperatures	TurnOnAirconditioner(M4)	ACTurnedOn(M4)
			TurnOffAirconditioner(M4)	ACTurnedOff(M4)
	WaterKettle	A device for boiling water	BoilWater(M2)	FinishBoilingWater(M3)
	DoorSensors	A sensor for door state	GetDoorState(M2)	StateObtained(M2)
	BodySensors	A sensor for body movement	—	BodyMovement(M2)
	AirSensor	A sensor for air quality	GetAirQuality(M2)	DataObtained(M2)
	TV	TVs in the laboratory	TurnOnTV(M3)	TVTurnedOn(M3)
			TurnOffTV(M3)	TVTurnedOff(M3)
	Light	Lights in the laboratory	TurnOnLight(M4)	LightTurnedOn(M3)
			TurnOffLight(M4)	LightTurnedOff(M3)
Social Resource	Worker	A person who can perform a certain task	GetItem(M5)	FinishTask(M5)
			DeliverItem(M5)	
			PerformTask(M5)	

define the event of the light. A light sensor can monitor the on state of the light.

The worker, as a typical type of social resource, is defined using *M5*. In our environment setting, when a service (e.g. $GetItem$) is requested, the crowdsourcing platform assigns a task such as getting item to a selected worker.

2 Results of Usability Study

All the participants completed the questinnaire and Figure 1 is the generated portfolio diagram. In the diagram, PQ indicates the pragmatic quality, i.e., the evaluation to the practicality of the tool, while HQ indicates the hedonic quality, i.e., the evaluation to the user experience of the tool. The dark blue point in the figure indicates the mean value of the joint graph, and the light blue rectangle indicates the confidence region.

Figure 2 shows the four detail metrics of PQ, HQ-Identity (HQ-I), HQ-stimulation (HQ-S), and Attractiveness (ATT). Among them, HQ-I and HQ-S are two subdivisions of HQ, which indicate the tool recognition and the tool novelty respectively. ATT indicates the tool attractiveness. The result shows that the novelty and attractiveness of the tool are generally better than the practicality and recognition. In addition, Figure 3 illustrates the statistical breakdown of the adjective-pairs for the above four metrics. It indicates that the tool is more biased towards a professional workflow tool from the perspective of the participants, but the tool has a relatively good organizational structure. The participants generally recognize the value of the tool, and believe the tool has a certain degree of innovation. In addition, this tool is attractive to the participants, but the aesthetics of the interface still needs to be improved.

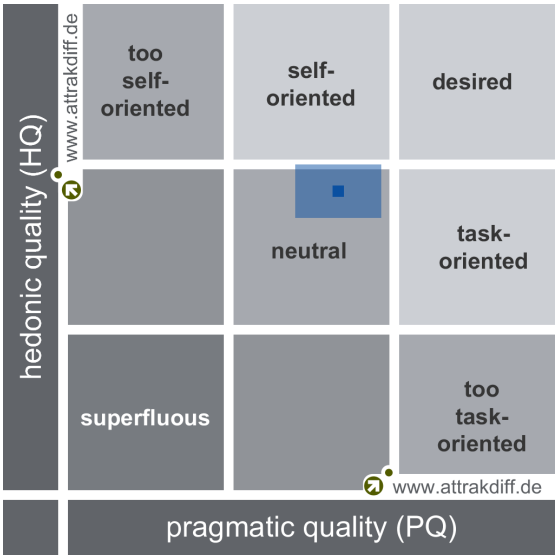

Fig. 1. Portfolio Diagram by $AttrakDiff^{TM}$

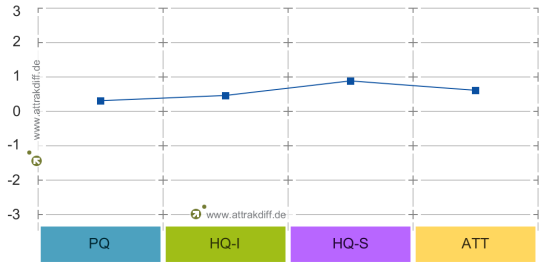

Fig. 2. Mean values of the four metrics in $AttrakDiff^{TM}$

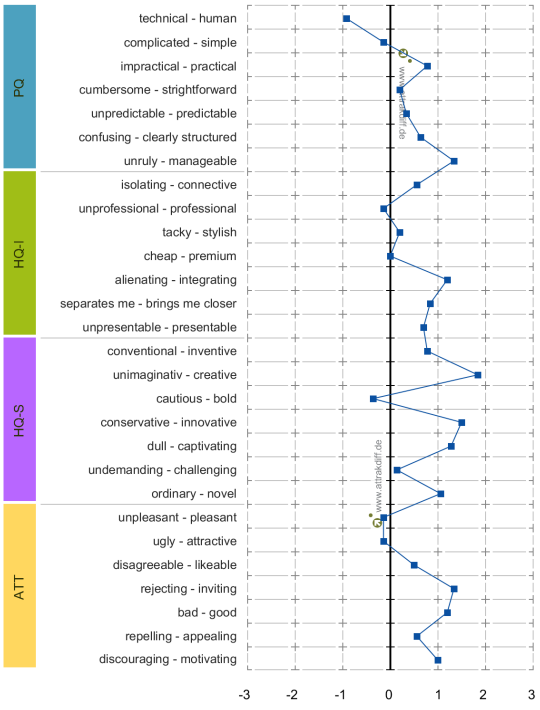

Fig. 3. Mean values of the $AttrakDiff^{TM}$ adjective-pairs

3 Results of Scalability Study

Table 2 is the result of the real execution with two application instances. In this table, *Service/Event* means the pair of the service and the corresponding event of a resource. The service can be none indicating the application is started by the event. $Instance$ denotes the different instance identifier marked as A and B. T_c means the collaboration time in millisecond between two resources. The last four columns denote the total execution time (T_e), the total collaboration time (T_{tc}), the total waiting time (T_{tw}) and the total transition time (T_{tt}). In particular, the time wrapped in parentheses before the first service of #4, #5, #6, #7, #10, #11, #12, #14 indicates the scheduling time taken by a user or timer to start the application. In addition, the time wrapped in parentheses in T_c indicates the waiting time. It should be noticed in #7 and #14, there exist discontinuous resource collaboration, e,g., making an online store order may not immediately trigger the event of receiving the goods arrival message. Therefore, we marked the T_c as "~" and it was not counted into T_{tc}.

Figure 4 shows the result charts of the first simulation scheme. The blue line and green line represent the waiting time and the transition time respectively. The sum of the values of the green and the blue lines represents the collaboration time. Figure 5 shows the result charts of the second simulation scheme.

TABLE 2
Result of Real Execution with Two Application Instances

Sce.	Instance	Service	/	Event	T_c(ms)	Service	/	Event	T_c(ms)	Service	/	Event	T_c(ms)	T_e(ms)	T_{tc}(ms)	T_{tw}(ms)	T_{tt}(ms)
#1	A		/	MessageReceived	14.3	GetItem	/	FinishTask	12.3	DeliverItem	/	FinishTask	13.0	SendMessage	/	MessageSent		91509.0	39.7	14.4	25.3
	B		/	MessageReceived	30023.3(29987.0)	GetItem	/	FinishTask	9.0	DeliverItem	/	FinishTask	12.3	SendMessage	/	MessageSent		121537.0	30044.7	30004.3	40.3
#2	A		/	HumanDetection	8.7	Punch-In	/	FinishPunchingIn	13.7	TurnOnAirCleaner	/	AirCleanerTurnedOn						4288.0	22.3	12.3	10.0
	B		/	HumanDetection	2989.3(2894.0)	Punch-In	/	FinishPunchingIn	10.0	TurnOnAirCleaner	/	AirCleanerTurnedOn						7340.3	2999.3	2902.3	97.0
#3	A		/	HumanDetection	7.7	Punch-In	/	FinishPunchingIn	17.0	TurnOnLight	/	LightTurnedOn						4288.7	24.7	12.7	12.0
	B		/	HumanDetection	2878.7(2813.3)	Punch-In	/	FinishPunchingIn	11.7	TurnOnLight	/	LightTurnedOn						7270.7	2890.3	2817.3	73.0
#4	A	(5.0ms)GetDoorState	/	StateObtained	11.7	TurnoffLight	/	LightTurnedOff										1220.0	16.7	10.3	6.3
	B	(123.3ms)GetDoorState	/	StateObtained	1108.3(1017.7)	TurnoffLight	/	LightTurnedOff										2435.7	1231.7	1136.4	95.3
#5	A	(11.0ms)MakeOrder	/	OrderCompleted	8.0	MakeCoffee	/	FinishMakingCoffee	11.7	GetItem	/	FinishTask	101.0	DeliverItem	/	FinishTask		120202.7	131.7	110.0	21.7
	B	(914.0ms)MakeOrder	/	OrderCompleted	59759.7(596683.0)	MakeCoffee	/	FinishMakingCoffee	174.0	GetItem	/	FinishTask	224.7	DeliverItem	/	FinishTask		180513.0	61072.3	60943.3	129.0
#6	A	(4.0ms)GetDoorState	/	StateObtained	9.7	TurnOnLight	/	LightTurnedOn										1216.0	13.7	9.0	4.7
	B	(123.3ms)GetDoorState	/	StateObtained	1110.7(1024.3)	TurnOnLight	/	LightTurnedOn										2439.0	1234.0	1128.7	105.3
#7	A	(13.0ms)MakeOrder	/	OrderCompleted	~		/	MessageReceived	13.3	GetItem	/	FinishTask	171.0	DeliverItem	/	FinishTask		62508.3	197.3	177.6	19.7
	B	(923.0ms)MakeOrder	/	OrderCompleted	~		/	MessageReceived	58912.3(58712.0)	GetItem	/	FinishTask	148.3	DeliverItem	/	FinishTask		132594.0	59983.7	59795.7	188.0
#8	A		/	MessageReceived	11.3	GetItem	/	FinishTask	23.3	DeliverItem	/	FinishTask						90232.3	34.7	22.7	12.0
	B		/	MessageReceived	60270.7(606133.3)	GetItem	/	FinishTask	29.3	DeliverItem	/	FinishTask						120345.0	60300.0	60147.3	152.7
#9	A		/	HumanDetection	7.7	Punch-In	/	FinishPunchingIn	11.0	TurnOnLight	/	LightTurnedOn						4243.7	18.7	9.7	9.0
	B		/	HumanDetection	2920.7(2912.0)	Punch-In	/	FinishPunchingIn	9.7	TurnOnLight	/	LightTurnedOn						7273.0	2930.3	2891.7	38.7
#10	A	(12.3ms)MakeOrder	/	OrderCompleted	10.3	PrintFile	/	FinishPrintingFile	13.0	GetItem	/	FinishTask	225.7	DeliverItem	/	FinishTask		81369.0	261.3	235.3	26.0
	B	(932.3ms)MakeOrder	/	OrderCompleted	23119.7(22182.3)	PrintFile	/	FinishPrintingFile	358640.(35713.7)	GetItem	/	FinishTask	271.3	DeliverItem	/	FinishTask		115074.7	60187.3	59978.3	209.0
#11	A	(12.6ms)InitiateMeetings	/	Notification	157.7	TurnOnAirCleaner	/	AirCleanerTurnedOn													
					40.3	TurnOnLight	/	LightTurnedOn													
					154.0	TurnOnTV	/	TVTurnedOn													
					97.3	MakeOrder	/	OrderCompleted	10.3	MakeCoffee	/	FinishMakingCoffee	10.7	GetItem	/	FinishTask	90.0	DeliverItem	/	FinishTask	123611.7	572.9	521.3	51.6
	B	(810.0ms)InitiateMeetings	/	Notification	1276.7(1201.0)	TurnOnAirCleaner	/	AirCleanerTurnedOn													
					1230.0(1093.0)	TurnOnLight	/	LightTurnedOn													
					22.0	TurnOnTV	/	TVTurnedOn													
					858.7(814.7)	MakeOrder	/	OrderCompleted	583600.(582237.0)	MakeCoffee	/	FinishMakingCoffee	183.0	GetItem	/	FinishTask	121.3	DeliverItem	/	FinishTask	183877.0	62861.7	62431.7	430.0
#12	A	(12.3ms)MakeOrder	/	OrderCompleted	8.0	MakeCoffee	/	FinishMakingCoffee	11.7	GetItem	/	FinishTask	68.7	DeliverItem	/	FinishTask					120124.3	100.7	83.4	17.3
	B	(922.6ms)MakeOrder	/	OrderCompleted	59793.0(58981.0)	MakeCoffee	/	FinishMakingCoffee	97.0	GetItem	/	FinishTask	137.0	DeliverItem	/	FinishTask					180386.0	60949.6	60790.3	159.3
#13	A		/	Notification	6.7	MakeCoffee	/	FinishMakingCoffee	11.7	GetItem	/	FinishTask	57.7	DeliverItem	/	FinishTask					120123.0	76.0	58.7	17.3
	B		/	Notification	59930.0(596683.0)	MakeCoffee	/	FinishMakingCoffee	96.7	GetItem	/	FinishTask	136.0	DeliverItem	/	FinishTask					180327.7	60162.7	60050.3	112.3
#14	A	(9.0ms)InitiateMeetings	/	Notification	~		/	HumanDetection	7.0	Punch-In	/	FinishPunchingIn									7369.3	16.0	14.3	1.7
	B	(319.0ms)InitiateMeetings	/	Notification	~		/	HumanDetection	885.7(864.3)	Punch-In	/	FinishPunchingIn									10400.3	1204.7	1163.0	41.7

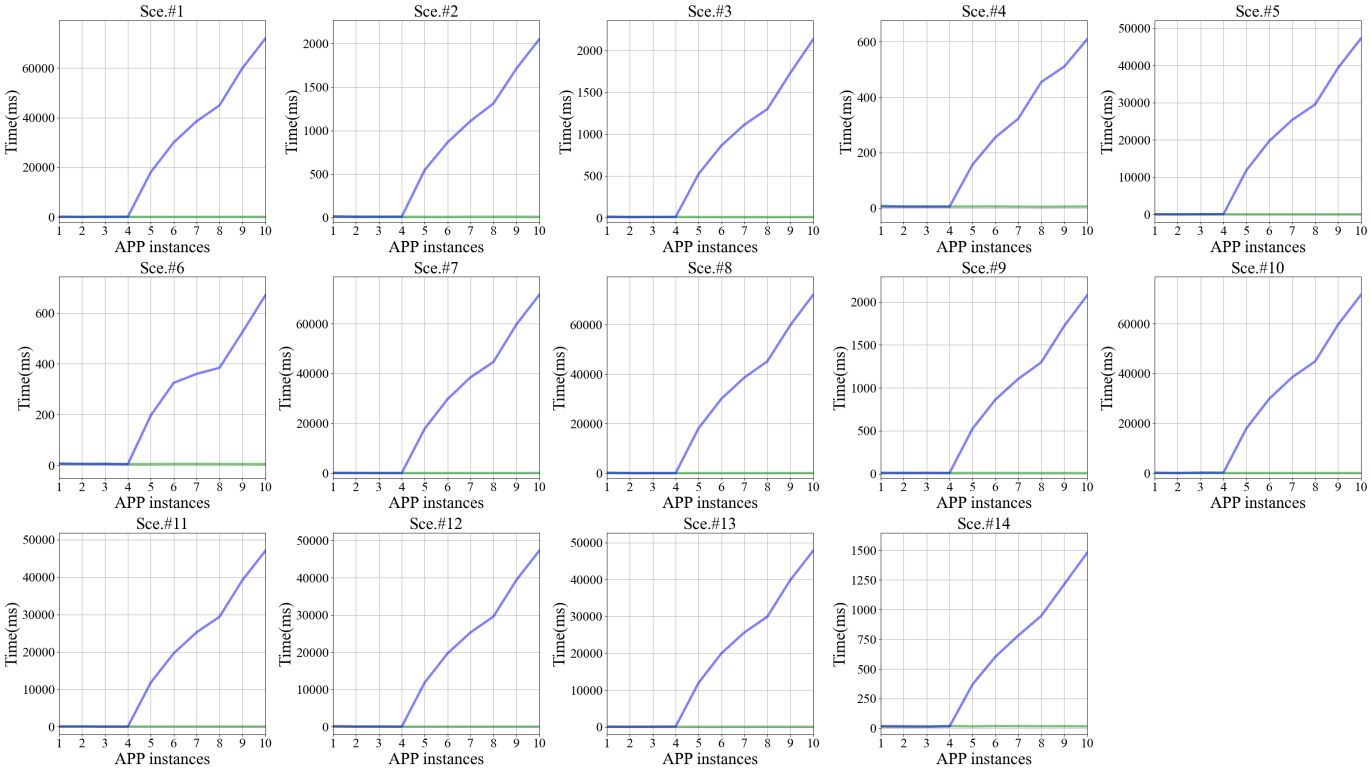

Fig. 4. Result Charts of the First Simulation Scheme

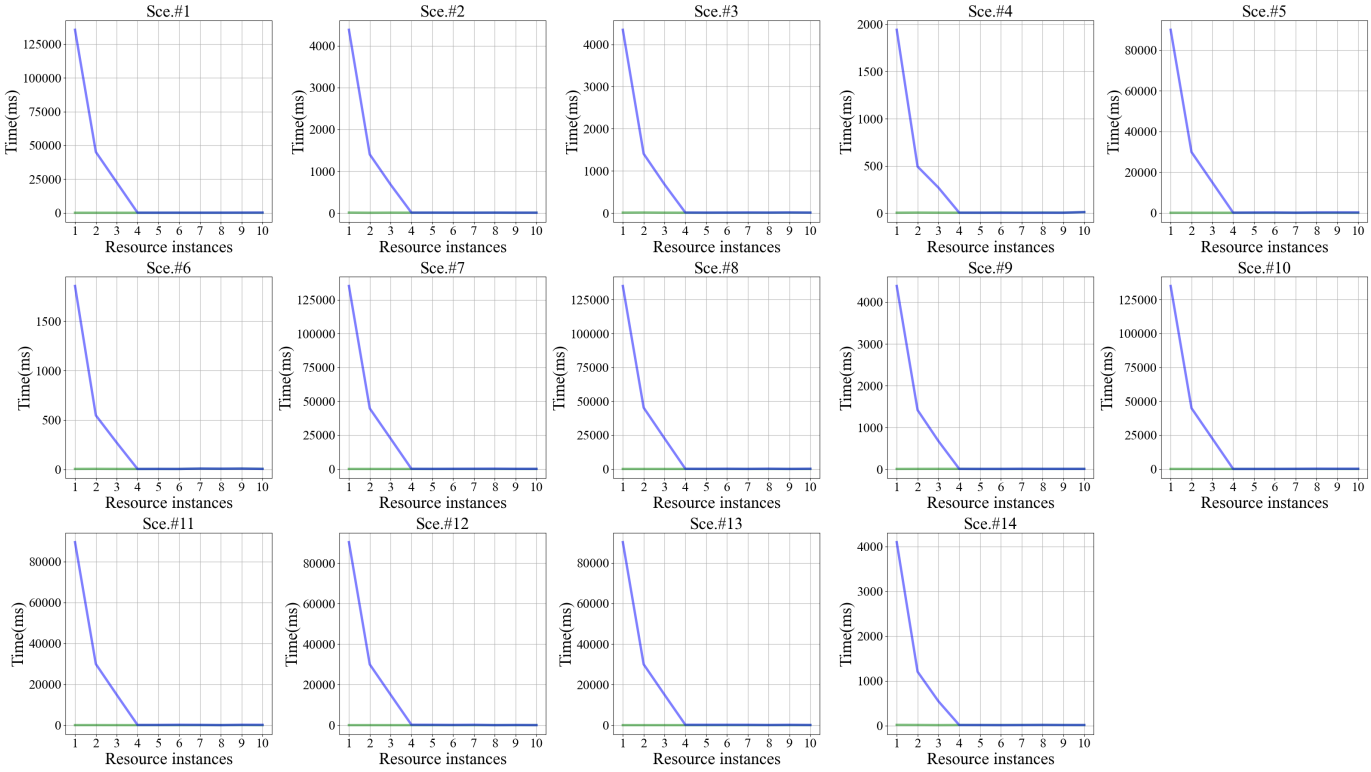

Fig. 5. Result Charts of the Second Simulation Scheme

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