White Paper: Digital Twin Optical Network as an Enhanced Network Operation

OIF-ENO-Applic-DT-01.0

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ABSTRACT: This white paper addresses the interoperability requirements for digital twin optical network as an enhanced network operation that interact between optical networks and management-control systems. It will specify the relationship between the digital twin optical network and MC system, interface operation, input/output data requirements and collection which is an important step as a start for standardizing digital twin optical networks for intelligent control.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 Introduction

1.1 Problem Statement

The large-scale optical network is becoming increasingly complex, and there is an urgent need for automated services and intelligent operations.

It is difficult to get guaranteed reliability, improved low management and control efficiency, and greater network tolerance. The maturity of emerging technologies, such as artificial intelligence, machine learning, and big data, provides technical support for the development of digital twin optical networks.

The operation and maintenance of the optical network are facing the pressure of improvement in perception, interaction, simulation, analysis, diagnosis, and prediction. The digital twin optical network can serve as an alternative to the physical entity for optical networks. The great significance of introducing digital twin technology is that of providing a digitally mirrored, high-precision reproduction of the features of physical a optical network in the digital world.

Applying digital twin technology to conduct data collection, performance visualization, fault tracing, dynamic tuning, and other aspects of optical network management can further enhance the ability for planning, construction, maintenance, optimization, and operation of the optical network.

There is consensus that the data on which those algorithms operate is appropriate for standardization and that is under study in at least one SDO (ITU-T).

This white paper addresses the functional requirements as well as data requirements to support interoperability when applying the digital twin optical network for enhanced network operation. It is useful for analyzing, diagnosing, emulating and controlling the optical network based on data, model and interface, to achieve the real-time interactive mapping between the optical network and the digital twin optical network.

1.2 Scope

This white paper identifies the functions, interfaces, and associated data requirements to support the digital twin optical network for enhanced network operation. It collects a set of use cases for the digital twin optical network. Detailed specifications are beyond the scope of this white paper.

It describes the requirements and architecture of the digital twin optical network as an enhanced network operation. The scope of this white paper includes the following items:

- General architecture of digital twin optical network;
- Functional requirements of digital twin optical network;
- Data requirements and interfaces related to the use cases.

The use cases in this document are designed to illustrate only some of the possible applications of digital twin(DT) optical network. The list is not exhaustive or final; there are many other possible applications and more may be investigated in the future.

The use cases in this white paper are for optical networks carrying only signals using coherent modulation. In case of networks carrying otherwise modulated signals, additional attributes may be necessary.

The use cases include: rapid service deployment, performance evaluation and optimization, fault localization and simulation, network planning and simulation and cutover scheduling and risk assessment. There are many other possible applications and more may be investigated in the future.

1.3 Relationship to Other Standards Bodies

This document will analyze available standards to determine any gaps and missing pieces from solution point of view and develop or work with other standard bodies to address them.

Following is the list of SDOs and their corresponding areas/projects that are candidates for co-operation/reuse.

1) ITU-T SG15
2) ITU-T SG13

1.4 List of Contributors

We acknowledge and thank the work from the following contributors.

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2 Digital Twin optical network as an Enhanced network operation

Enhanced network operations are needed by some applications for network planning, forecasting demand, predicting errors and faults monitoring alarms and error conditions, and optimization [3]. Some applications may explore new technology such as digital twin technology for simulation, analysis, prediction, and modelling.

2.1 ITU-T Architecture of management-control for transport networks

Figure 1 shows the management-control continuum concept and its relationship with transport resources [1]. The management & control(MC) system can be software defined network(SDN) MC system or automatically switched optical network(ASON) MC system. Other MC systems such as network management system(NMS)/element management system(EMS) that include traditional fault, configuration, accounting, performance, and security management(FCAPS) functions can also implement MC functions. An SDN controller supports standard northbound and southbound interfaces to transport resources and to other SDN controllers. The ONF TAPI ([5]) is an instance of these interfaces.

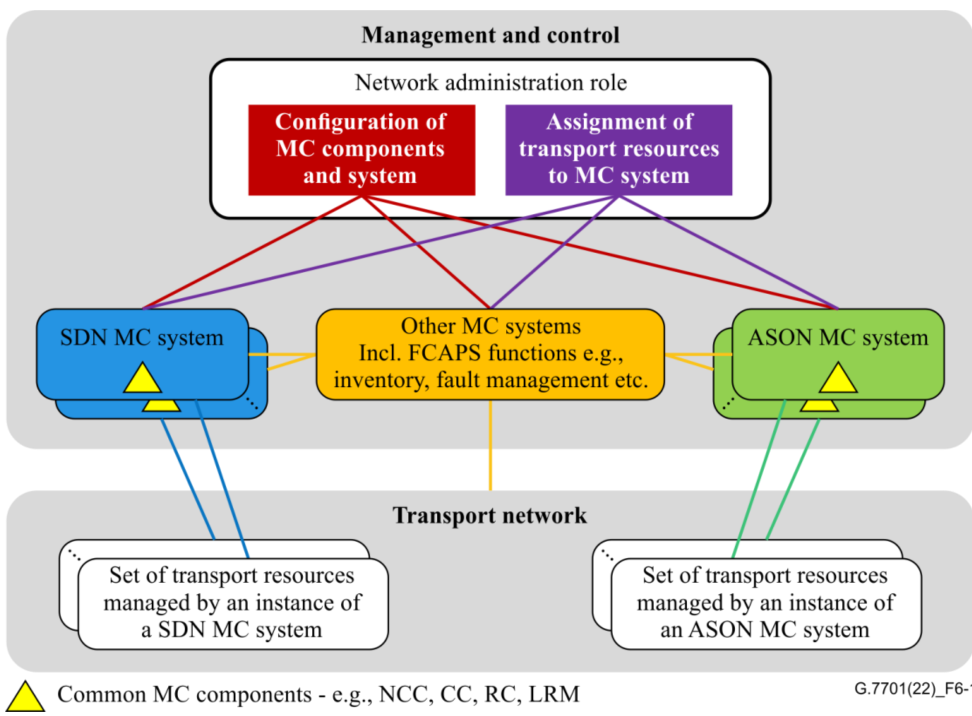

Figure 1 Architecture of management-control for transport networks (Figure 6-1/G.7701)

2.2 Enhanced network operations

Enhanced network operations defined by the OIF white paper "OIF-ENO-Applic-AI-01.0" are external to MC systems as shown in Figure 2. To improve maintenance efficiency, enhanced network operations should support the capabilities for perception, interaction, simulation, analysis, diagnosis, prediction, and optimization.

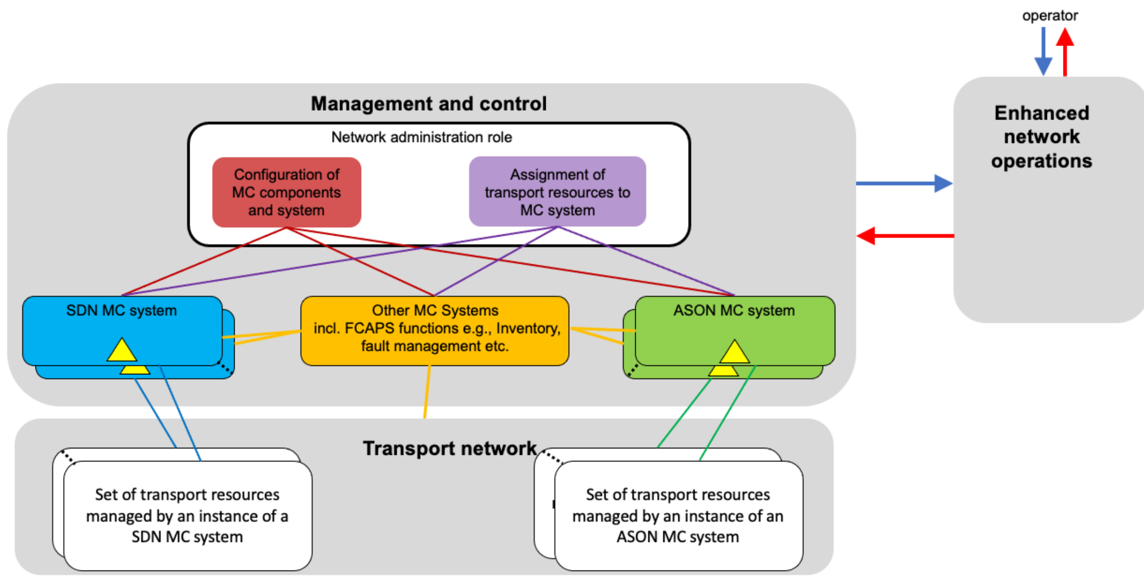

Figure 2 Enhanced network operations and MC systems

2.3 Digital Twin optical network as an enhanced network operation

Enhanced network operations may be implemented with digital techniques for optical networks. Digital twin optical network can interact with MC systems (e.g., SDN controllers) by combining with the architecture shown in Figure 3. Figure 3 shows the example of Digital twin optical network as an enhanced network operation. It illustrates some models of the digital optical network. In general, the models in Figure 3 could be OSNR model, fiber model, BER model, OA model, service model, abnormal model, etc.
The simulation function provides the service simulation required for the digital twin optical network. According to different scenarios, the simulation function identifies, splits, and combines basic and functional models to realize simulation service. In general, the simulation function could be service simulation function, performance simulation function, fault simulation function, etc.

The validation function provides the validation service required for digital twin optical network. Based on digital twin models, the validation function can sufficiently validate prediction, scheduling, configuration, optimization to ensure effective and reliable control of the optical network. In general, the validation function could be service validation, strategy validation, fault validation, etc.
The digital twin optical network can organize and orchestrate models. The simulation function and the validation function can orchestrate digital twin models to support various use cases. By the collection of corresponding optical network data, the simulation function outputs the simulation results to the validation. After being fully validated by the validation function in the digital twin optical network, the simulation results are fed back to the customer's application or distributed to the optical network through MC system.

The optical network is a physical entity in the physical space that needs digital twin simulation, including optical devices, optical module, boards, devices, services and networks. The digital twin of optical networks is the main body that implements digital twin simulation of optical networks from devices, services, and networks. Various data models built in digital twin optical networks can be flexibly combined to simulate optical devices, optical module, boards, devices, and services. The digital twin optical network can support innovative technologies and applications in various aspects such as planning, construction, maintenance, optimization, and operation.

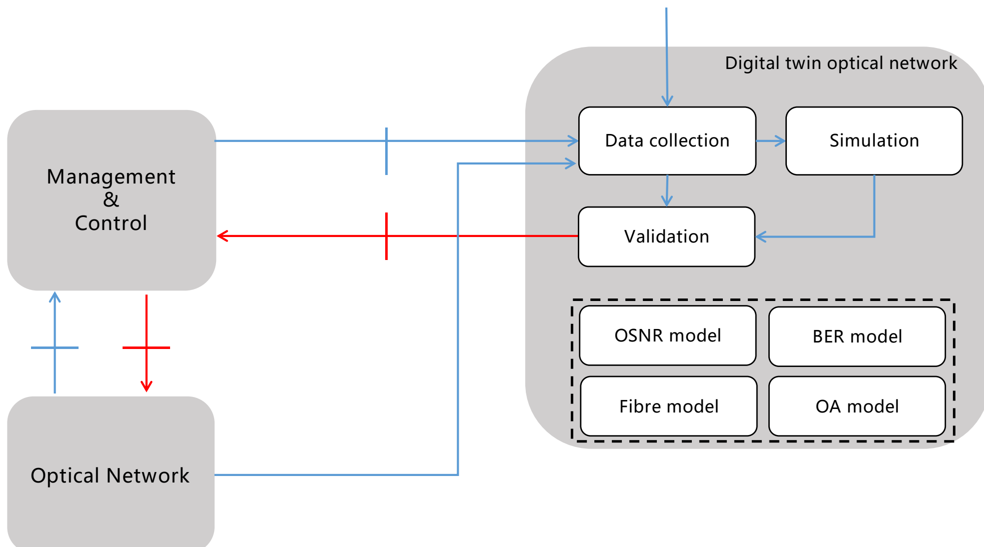

Figure 3 Example of Digital twin optical network as an enhanced network operation

The optical network digital twin system has greater requirements for data collection period, accuracy, and dimensions: traditional data collection methods cannot effectively meet the requirements of the digital twin optical network.

Telemetry is an effective method for data collection at both optical and electrical layers, compared to traditional long period collection methods such as simple network management protocol(SNMP), telemetry is able to more accurately locate the time of the fault occurrence. With the increasing size of optical networks, the data generated by the optical network is also becoming massive. It is a great challenge for collection, management, and analysis capabilities of existing control systems.

For network operators, in order to cope with the massive data reporting represented by telemetry technology, telemetry can provide efficient data collection, storage, processing, calculation, and quickly and accurately provide a data foundation for the digital twin system. Enhancing visualization capabilities and dynamically mapping the visualization of service and network entity in the digital twin of physical entity optical networks, it not only intuitively expresses the results of perception, analysis, and simulation, but also dynamically presents the validation process of the twin model, making it convenient for users to monitor network status. The dynamic change process of optical network performance can display the variation process of performance parameters such as optical power, optical signal to noise ratio(OSNR), and bit error ratio(BER), as well as simultaneously display the real-time dynamic refresh process of optical power and OSNR in seconds.

The digital twin optical network can support a physical entity in physical space to be mapped into digital twin modeling, including optical devices, optical modules, boards, devices, systems, and networks. The digital twin optical network supports physical entity and logical entity modeling, and is able to continuously iterate, optimize, and simulate the model.

Table 1 Reference point – example data

Example Inputs	Example Outputs
• Network topology • Resource utilization • Alarms • Performance • Service level agreement(SLA) • Intent	• Service configuration • Connection changes • Traffic forwarding changes • Network configuration changes

From the optical network, alarms and performance can be collected to MC systems, then passed by to digital twin optical network. Input to digital twin optical network may accept service intent from the operators.

Outputs of the digital twin optical network can be service optimization configurations that result from the simulation function. Commands from MC systems can be new network connection setup or optical power adjustment.

2.4 Data Collection Origin

The data collection origin could include optical components, fibre, equipments, resources, configurations, performances, alarms, and states. The optical components could be compound components of a sequence of active or passive components. Table 3 below provides an overview of data collection for all use cases.

The selection and usage of these data depend on different use cases. The data collection includes but not limited to:

- Configuration data: the configuration information of optical transport unit(OTU), optical layer, service, etc.
- Performance data: the performance of optical components, ports, links and service, etc. This includes working performance as well as performance characteristics of components. These characteristics are preferably performance curves depending on e.g. load or SNR which have to be made available to the digital twin optical network.
- Alarm data: the failure of optical modules, optical components, ports, fibre and service, etc.
- State data: the protection state of network, etc.
- Optical components data: the data of laser, amplifier, splitter, and wavelength selective switch(WSS) components.
- Fibre data: fibre segment, fibre length, fibre type, optical time domain reflectometer (OTDR).

Table 2 Data collection for all use cases

		Data type	Data origin
Equipment data		NE: NE id, NE type	Get from the MC
		Board id, board type, rack, sub-rack	
Resource data	Ports	Port id, port type, ports rate	Get from the MC
	links	Source and sink of links, link rate, link direction	Get from the MC
		Channel, time-slot	Get from the optical network
Configuration data	Optical components	Central-wavelength, modulation, forward error correction(FEC), optical module type	Get from the MC
		Optical amplifier type, gain, gain slope, built-in variable optical attenuator(VOA) attenuation	
		Channel interval of splitter	
		Channel configuration of reconfigurable optical add-drop multiplexer(ROADM)	
	Service configuration	Service type, protection data, ports of service, optical data unit-k(ODUk) layer data, optical channel(OCh) layer data, ODUk type, ODUk sub-network connection, service bandwidth	Get from the MC
Alarm data	Alarm event	Current alarm and history alarm, alarm source, alarm type, alarm level, alarm state, reason, begin time, end time	Get from the optical network
Performance data	Optical module	Laser operating temperature, laser bias, voltage, input power, output power, dispersion compensation value, differential group delay, OSNR, FEC BER before correction, state of Polarization (SOP)	Get from the optical network
	Port performance	Port utilization, sending/receiving packages, bit error rate, port peak rate, latency, polarization mode dispersion (PMD), Polarization state	
	Link performance	Bandwidth utilization	

	Service performance	Jitter, packet loss, latency, error vector magnitude (EVM)	
State data	Protection state	Protection state, switching time	Get from the optical network
	Physical state	NE state, board state, port state, optical module state, laser state	Get from the optical network
Optical components data	active devices	Laser, modulator, amplifier, splitter, OTDR	Get from the optical network
	WSS	Central wavelength, passband width, passband insertion loss, pass band, insertion loss	Get from the optical Network
Fibre data		Fibre length, fibre type (G.652, G.653, G.654E, etc.) , loss, dispersion, external vibration event, number of fibre segment	Get from MC

3 Use Cases of Digital twin optical network

This section provides use cases of digital twin optical network as an enhanced network operation. The interoperability requirements (input/output data, interfaces, functions) are specified.

3.1 Use Case #1: Rapid service deployment

1. Overview

With the increase of optical network traffic and the rapid growth of the amount of optical network nodes, traditional optical performance monitoring (OPM) and analysis has difficulty to meet rapid service deployment requirements. Especially under dynamic service deployment situations, improved methods for analysis of optical performance monitoring will greatly affect the rapid deployment of services.

Digital twin optical networks enable rapid service deployment by predicting optical performance for different service options over a given network. Digital twin optical network supports rapid performance perception ability and on-line service simulation. It can emulate the performance of different potential paths. When customer intent is inputted, digital twin optical network can select the optimal path based on history data of emulated paths.

2. Interaction with enhanced network operations

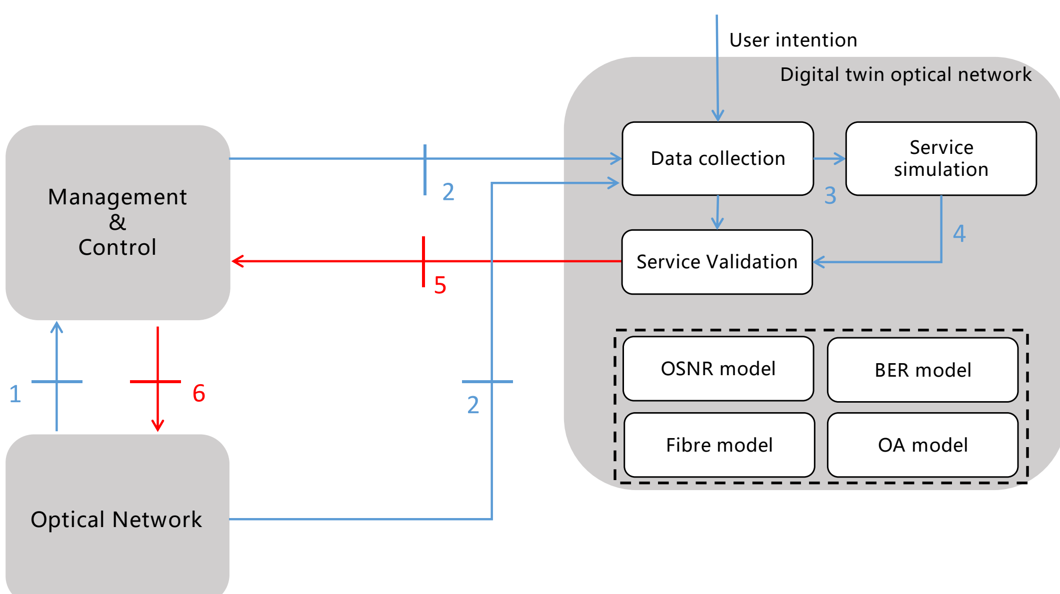

Figure 4 Interaction with rapid service deployment

The detailed description of each step in **Error! Reference source not found.** is as follows:

Step 1: MC system collects necessary data from optical network by a collection method.

Step 2: MC system provides some data as shown in Table 3 (e.g., topology information, NE Information, optical power, BER, delay, performance data,component performance characteristics, and bandwidth) as input to digital twin optical network.

Step 3: The data collector synchronizes real-time parameters such as input power and output power, BER, optical device related performance, as well as path latency, topology resources, service resources, bandwidth resources, and other resources information on the optical network, constructing a service performance and latency in a timely manner.

Step 4: Based on user intentions, combined with current network states such as resource utilization, performance, and timely delay maps, the optimal routing scheme is calculated by setting the service simulation function with routing strategies (such as minimum latency, minimum hop count path, optimal SLA, etc.).

Step 5: Based on real-time network data, including optical power, OSNR, the service validation function calculates the impact of simulated services, and simulate adjusting the route. Finally, the digital twin optical network sends optimal service configuration requirements to MC system.

Step 6: MC system will configure the optimal routing and end-to-end service configuration to the optical network.

3. Use Case driven requirements

- Input data requirements

a) Requires collection of network topology, NE configuration, fibre types and service information.

b) Requires collection of performance data including optical power, optical amplifier performance, etc.

c) Service requirements with service type, SLA parameter.

Table 3 Input of data collection

Data		**Description**
Topology	Topology ID	Topology represents link and subnetwork (switching) resources. These resources may be abstract or supported by software and hardware implementations. The topology identifier is unique in the context of some scope which could be global.
	Number of fibre segments	Number of fibre segments of each optical channel.
	Fibre types	G.652, G.653, G.654E, etc.
	Fibre length	The cable length between two adjacent optical cable splice closures.
	Wavelength	Wavelength refers to the distance traveled by a wave during one vibration cycle.
	Frequency	The frequency of light waves refers to the number of times they vibrate per unit time.

	Number of optical amplifier(OA)	Number of optical amplifiers of each optical channel.
Performance Data	Input optical power	The signal optical power at the input for a specified signal optical power.
	Output optical power	The signal optical power at the output for a specified signal optical power.
	Gain	In an OA, the increase of signal optical power from the input reference point R' to the output reference point S', expressed in dB.
	Attenuation	The attenuation at specific wavelength λ between two cross sections 1 and 2 separated by distance L of a fibre is defined as: $A(\lambda) = 10\log\frac{P_1(\lambda)}{P_2(\lambda)}(\mathrm{dB})$ where P1(λ) is the optical power traversing cross section 1, and P2(λ) is the optical power traversing cross section 2 at the wavelength λ.
	Sensitivity	The minimum optical power associated with the input signal, immediately before the input connector, necessary to achieve a fixed BER value
	Overload	The input power at a specified BER (e.g., 10^{-12}) and at a specified bit rate.
	Link latency	The time it takes for a specific package of data to rotate around to the read/write head.
	Error ratio of optical channel	Optical channel error rate refers to the ratio of the number of bits misjudged or missed by the receiving end to the total number of bits in an optical communication system
	Attenuation of Optical amplifier	Attenuation of optical amplifier refers to the attenuation of power during propagation in optical amplifier, usually expressed in decibels (dB).
	OSNR of transmitter	At the output port, the optical OSNR is the ratio of the signal power in the wanted channel to the highest noise power density within the channel frequency range.
	Noise Figure	The Noise Figure is used to measure the noise performance of an amplifier or system. It represents the ratio between the additional noise introduced by the amplifier (or system) and the noise introduced by the ideal amplifier.
	BER vs. OSNR	The relationship between pre-FEC bit error ratio (BER) or Q-factor and optical signal-to-noise ratio (OSNR)
	Reference power	Reference power of an optical module is a standard or benchmark value used for measuring and calibrating the optical power of the optical module.
Service bandwidth		The bandwidth allocated to the service.
Routing policy		The minimum delay, the best performance path, the best quality assurance.

- Processing requirements

a) Based on real-time optical power and OSNR, the digital twin optical network can evaluate the current service quality.
b) The digital twin optical network can set up optical fibre model, OSNR model, bit error rate model, and optical amplifier model. Based on actual performance and component performance characteristics, the service simulation function can provide iterative model analysis and evaluate optimal model.
c) The digital twin optical network can get performance data need to be working performance as well as performance characteristic of components.
d) With respect to the characteristics of large scale and numerous types of network data, there are technical requirements for corresponding data processing technology, which can be storing, cleaning, querying, marking, and visualizing diverse data.
e) Simulating and debugging the pre-scheduled service, simulating service route, simulating SLA, simulating service delay.
f) The service validation function can simulate the impacts of simulated services on optical network.
g) The service validation function can calculate the optimal or suboptimal configuration scheme.
h) The service validation function can select service route based on customer intention based on resource utilization, resource balance, performance and delay to be considered as best strategy (minimum delay, best route, optimal performance path, optimal service quality assurance, etc.).
i) The digital twin optical network can effectively interact with MC system.

- Output data requirements

Table 4 Output of service validation

Data	Description
Service configuration of simulation scheme	The service configuration simulated by digital twin optical network

- Interface and function requirements

a) Get topology information.
b) Get NE information.
c) Get performance data.
d) Get component performance characteristics.
e) Get configuration data.
f) Set configuration data.

3.2 Use Case #2: Performance evaluation and optimization

1. Overview

Optical networks are facing numerous challenges due to performance degradation, such as faults in optical layer with wide-ranging impact, long processing cycles, high cost, and difficulties in predicting faults. Traditional maintenance methods are limited and can only detect the performance deterioration which the faults cause. There are potential risks because of limited ability to identify network performance deterioration in advance. Furthermore, subsequent fault processing and optimization scheme selection rely on human experience.

By applying digital twin to evaluation of optical network performance, abnormal performance location can be quickly identified and performance trends can be predicted in advance. At the same time, proactive network optimization can effectively improve the efficiency of optical network management and maintenance while further enhancing the level of intelligent network management.

2. Interaction with enhanced network operations

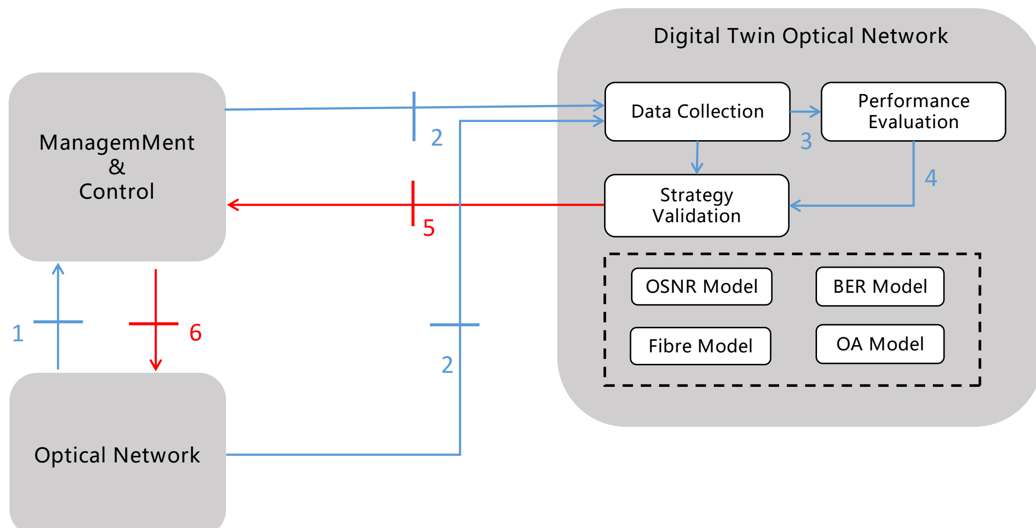

Figure 5 Interaction with performance evaluation and optimization

The detailed description of each step in Figure 5 is as follows:
Step 1: MC system collects necessary data from optical network by a collection method.
Step 2: MC system provides some data as shown in Table 5 (e.g., topology information, NE information, fibre information, optical power, delay, performance data, temperature, modulation format, warning threshold of network status) as input of digital twin optical network.

Step 3: The data collection synchronizes real-time parameters such as input power, output power, BER, and optical device related performance, as well as topology resources, service resources, bandwidth resources, and other resource information of the optical network.

Step 4: The performance trends and characteristics of network links, devices, wavelengths and services are predicted based on performance evaluation. Then the network status which can consider these factors comprehensively are evaluated. When the predicted performance is exceeding threshold, the optimization strategy for optical communication network performance is generated, such as adjusting optical power, regenerating signals, adding/activating equalization functions, and re-allocating routing wavelengths.

Step 5: The optimization strategy is verified by strategy validation function and it simulates the changes of network status, performance, and other parameters with optimizing the strategy. Finally, the digital twin optical network send optimization strategy to MC system.

Step 6: MC system will execute the optimization strategy to the optical network.

Step 7: The digital twin optical network compares working performance with DT prediction to assess and further improve DT accuracy.

3. Use Case driven requirements

- Input data requirements

a) Requires collection of topology Information, NE Information, fibre information, optical power, delay, actual performance data, , component performance characteristics, bandwidth, service information, temperature, modulation format, warning threshold.

b) Requires collection of performance data, such as optical power, gain, etc.

c) Requires collection of service information.

d) Requires warning threshold.

Table 5 Input of data collection

Data		**Description**
Topology	Topology ID	Topology represents link and subnetwork (switching) resources. These resources may be abstract or supported by software and hardware implementations. The topology identifier is unique in the context of some scope which could be global.
	Number of fibre segments	Number of fibre segments of each optical channel.
	Fibre types	G.652, G.653, G.654E, etc.
	Fibre length	The cable length between two adjacent optical cable splice closure.
	Wavelength	Wavelength refers to the distance traveled by a wave during one vibration cycle.
	Frequency	The frequency of light waves refers to the number of times they vibrate per unit time.
	Number of OA	Number of optical amplifiers of each optical channel.
Performance Data	Input optical power	The signal optical power at the input for a specified signal optical power.
	Output optical power	The signal optical power at the output for a specified signal optical power.
	Gain	In an OA, the increase of signal optical power from the input reference point R' to the output reference point S', expressed in dB.
	Attenuation	The attenuation at specific wavelength λ between two cross sections 1 and 2 separated by distance L of a fibre is defined as: $A(\lambda) = 10\log\frac{P_1(\lambda)}{P_2(\lambda)}(\mathrm{dB})$ where P1(λ) is the optical power traversing cross section 1, and P2(λ) is the optical power traversing cross section 2 at the wavelength λ.
	Sensitivity	The minimum optical power associated with the input signal, immediately before the input connector, necessary to achieve a fixed BER value

	Overload	The input power at a specified BER (e.g., 10^{-12}) and at a specified bit rate.
	Link latency	The time it takes for a specific package of data to rotate around to the read/write head.
	Error ratio of optical channel	Optical channel error rate refers to the ratio of the number of bits misjudged or missed by the receiving end to the total number of bits in an optical communication system.
	Attenuation of Optical amplifier	Attenuation of optical amplifier refers to the attenuation of power during propagation in optical amplifier, usually expressed in dB.
	OSNR of Transmitter	At the output port, OSNR is the ratio of the signal power in the wanted channel to the highest noise power density within the channel frequency range.
	Temperature	Environment temperature, device temperature.
	Modulation format	QPSK,16QAM
	Noise figure	The Noise Figure is used to measure the noise performance of an amplifier or system. It represents the ratio between the additional noise introduced by the amplifier (or system) and the noise introduced by the ideal amplifier.
	BER vs. OSNR	The relationship between pre-FEC bit error ratio (BER) or Q-factor and optical signal-to-noise ratio (OSNR)
	Reference power	Reference power of an optical module is a standard or benchmark value used for measuring and calibrating the optical power of the optical module.
Service information		Service routing, connection and service quality.
Routing Policy		The minimum delay, the best performance path, the best quality assurance.
Warning threshold		Warning threshold of network status can consider the performance trends of network link, device, wavelength and service comprehensively.

- Processing requirements

a) Based on input data, the performance evaluation function can predict the performance trends of network service, devices.

b) The digital twin optical network can set up optical fibre model, OSNR model, bit error rate model, optical amplifier model, performance prediction model, network evaluation model.

c) Based on the performance of network links, devices, wavelengths and services, the performance evaluation function can evaluate the network status which can be calculated by the performance trends of network links, devices, wavelengths and services comprehensively.

d) When the value of network performance is below the warning threshold, the network status is determined as poor.

e) The performance evaluation can generate the optimization strategy based on knowledge bases such as network optimization rules and expert experiences according to the network status.

f) With respect to the characteristics of large scale and numerous types of network data, there are technical requirements for corresponding data processing technology, which can be storing, cleaning, querying, marking, and visualizing diverse data.

g) The strategy validation function can simulate the impact of optimization strategy.

h) The digital twin optical network can effectively interact with MC system.

- Output data requirements

Table 6 Output of service evaluation

Data	Description
Optimization Strategy	Such as adjusting optical power, regenerating signals, adding/activating equalization functions, and re-allocating routing wavelengths, etc.

- Interface and function requirements

a) Get topology information.
b) Get NE information.
c) Get performance data.
d) Get component performance characteristics.
e) Get configuration data.
e) Get temperature data.
f) Get modulation format.
g) Get warning threshold of network status.
h) Set optimization strategy.
i) Set configuration data.

3.3 Use Case #3: Fault localization and simulation

1. Overview

It is possible for the digital twin optical network to replay existing optical network failures or simulate potential future faults, find the root cause, locate the root alarms, and provide maintenance suggestions to enhance the fast fault localization and self-healing capabilities of the optical network.

If for example, a link fails, a hardware condition is detected by the MC functions of NE, the digital twin optical network can select data models to quickly locate the root cause of the fault by combining fault rules and scenarios. The historical alarms within a set time period before the fault occurs can be traced back for simulation to verify maintenance suggestions. Then the digital twin optical network can transmit the self-repair plan to the management and control system for self-healing and restoration.

2. Interaction with enhanced network operations

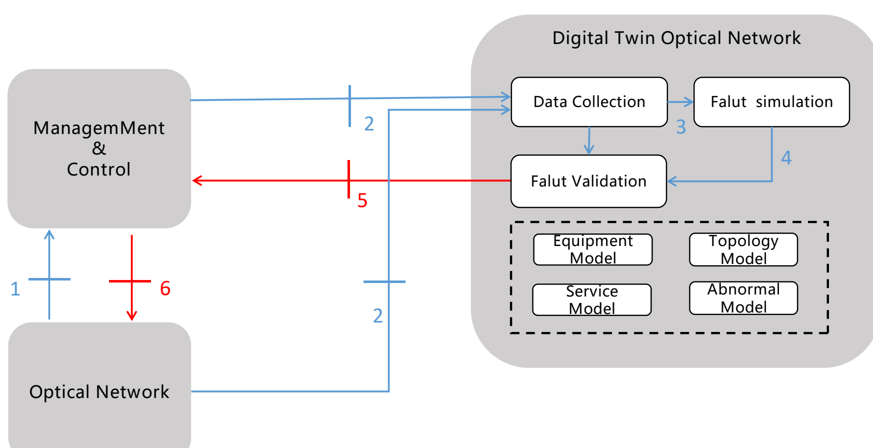

Figure 6 Interaction with fault localization and simulation

Step 1: MC system gets alarm and performance data from the optical network by a collection method.

Step 2: Management & C system provides some data (e.g., topology information, NE Information, alarm, performance, configuration data) as input of the digital twin optical network.

Step 3: When there are abnormalities/deterioration, alarm, the fault simulation function initiate fault localization analysis and troubleshooting processes. Combining topology, resources, and physical equipment, it selects and coordinates the data models according to hierarchical and topological rules. The digital twin optical network can combine the fault correlation rule library and fault scenario rule library of knowledge management to quickly locate the root cause of faults.

Step 4: The digital twin optical network, can trace back alarm and performance history within a set time period window before the occurrence of faults, and it can intelligently infer the location of the fault, determine the cause of the fault, develop self-healing plan and optimization strategy.

Step 5: The fault validation function verifies the self-healing plan and optimization strategy in the digital twin optical network, and output the root cause alarm, the self-healing plan and optimization strategy to the Management and Control system.

Step 6: MC system will execute the self-healing plan and the optimization strategy of the optical network.

3. Use Case driven requirements

- Input data requirements

a) Requires collection of topology, NE Information, alarm, performance and configurations.

b) Requires alarm include the location information from which the network element, card, port information can be extracted.

c) Requires collection of service information.

Table 7 Input of data collection

Data		Description
Topology ID		Topology represents link and subnetwork (switching) resources. These resources may be abstract or supported by software and hardware implementations. The topology identifier is unique in the context of some scope which could be global.
Alarm Data	Alarm ID	Indexed sequence number in time order.
	Alarm Level	The alarm severity assigned to the service affecting.
	Alarm Type	It identifies the active probable causes (failure) of the object.
	Alarm Name	The problem description for the entity.
	Alarm Code	It identifies the active probable causes (failure) of the object.
	Network Element ID	The identifier of Network Element.
	Object ID	The identifier of the object.

	Card ID	The line card may plug into equipment. The line card identifier is unique in the context of some scope.
	Port ID	It could be Null. The port can perform the termination and adaptation functions of one or more transport layers. It supports all transport protocols including circuit and packet forms. The port identifier is unique in the context of some scope
	Start Time	At the time the alarm is reported.
	End Time	At the end of time the alarm is cleared.
Performance Data	Performance Type ID	It is the layer-specific Performance data type.
	Network Element ID	The identifier of Network Element.
	Card ID	The line card may plug into equipment. The line card identifier is unique in the context of some scope.
	Port ID	The port can perform the termination and adaptation functions of one or more transport layers. It supports all transport protocols including circuit and packet forms. The port identifier is unique in the context of some scope.
	Performance Data Value	It contains the values of the PM parameters.
State	Route state	The route state is used to indicate whether or not the route is installed and working.
	Protection switch state	It is the protection switch state and revertible time of service.
	Physical state	It is used to indicate whether or not the physical resource is installed and working, including NE state, board state, port sate, component state.
Configurations		It should include service information: service name, service type, service ports, protection type, server layer of service, cross-connection information.

- Processing requirements

a) The digital twin optical network should support the processing of data input from the optical network or control system, such as labeling, classification, cleaning, etc., to improve efficiency for subsequent analysis and diagnosis.

b) The digital twin optical network should support dynamic acquisition of the state of the optical network, current alarm and current performance data from the optical network.

c) The digital twin optical network should support dynamic acquisition history alarm and history performance data from the MC system.

d) The digital twin optical network should analysis and diagnosis the correlation relationship between alarms and performance, and conducts correlation analysis through AI methods. It can establish correlation rules between root alarms and derivative alarms, identify root cause alarms and potential faults location.

e) The digital twin optical network should verify possible faults location to further accurately locate them. With the help of the simulation and safety of digital twin optical network, it is safety to simulate faults in digital twin optical network in order to find the physical fault location.

f) After determining the fault point, it can provide a recovery plan , and verify the recovery effect on the digital twin optical network.

g) The digital twin optical network should have dynamic and automatic time window configuration for alarm and performance data to support the digital twin optical network analyzing network operation state.
h) It should have a correlation analysis between alarm, performance, service and topology.
i) The digital twin optical network should verify the fault to support the simulation of faults on the digital optical network. For example, if a fault is simulated by the digital optical network, the digital optical network should present corresponding fault phenomena (alarm, performance, events) related to the fault.
j) The digital twin optical network should verify the effectiveness of the self-healing plan and optimization strategy until the optimal solution is found, and output the self-healing plan the optimization strategy to MC.

- Output data requirements

Table 8 Output of fault validation

Data	Description
Root alarm	The problems description of root alarm, i.e. root alarm ID, root alarm level, root alarm name, root alarm state.
Self-healing plan and optimization strategy of network	Self-healing plan makes it possible to avoid failures, such as re-allocating routing wavelengths, reschedule service path.

- Interface and function requirements

a) Get topology information.
b) Get NE information.
c) Get configuration data.
d) Get alarm data.
e) Get performance data.
f) Get component performance characteristics.
g) Set optimization strategy.
h) Set configuration data.

3.4 Use Case #4: Network planning and simulation

1. Overview

The planning and design of optical networks need to combine the requirements of network operators (i.e. network scale, network capacity, performance), actual optical fibre resource information, product characteristics of optical network equipment, and performance requirements to determine the optimal configuration scheme. The digital twin optical network can help to plan and simulate the excellent performance of network requirements .

Simulation of network planning based on the digital twin optical network can integrate various optical network equipment and fibre cable resource information. Based on the requirements of network topology, network equipment, and network parameters (such as fibre length, types, number of connectors, attenuation, etc.) inputted by planning and design staff, network performance parameters (such as OSNR, line error rate, flatness, margin of attenuation redundancy in optical cable routes, etc.) can be simulated and calculated. Network equipment configuration or parameter optimization suggestions can be provided with the optimal network planning scheme.

The digital twin optical network can provide simulation of network planning to simulate the actual network environment and equipment configuration. The configuration scheme and network planning scheme generated by the digital twin optical network can be directly synchronized with the MC system.

2. Interaction with enhanced network operations

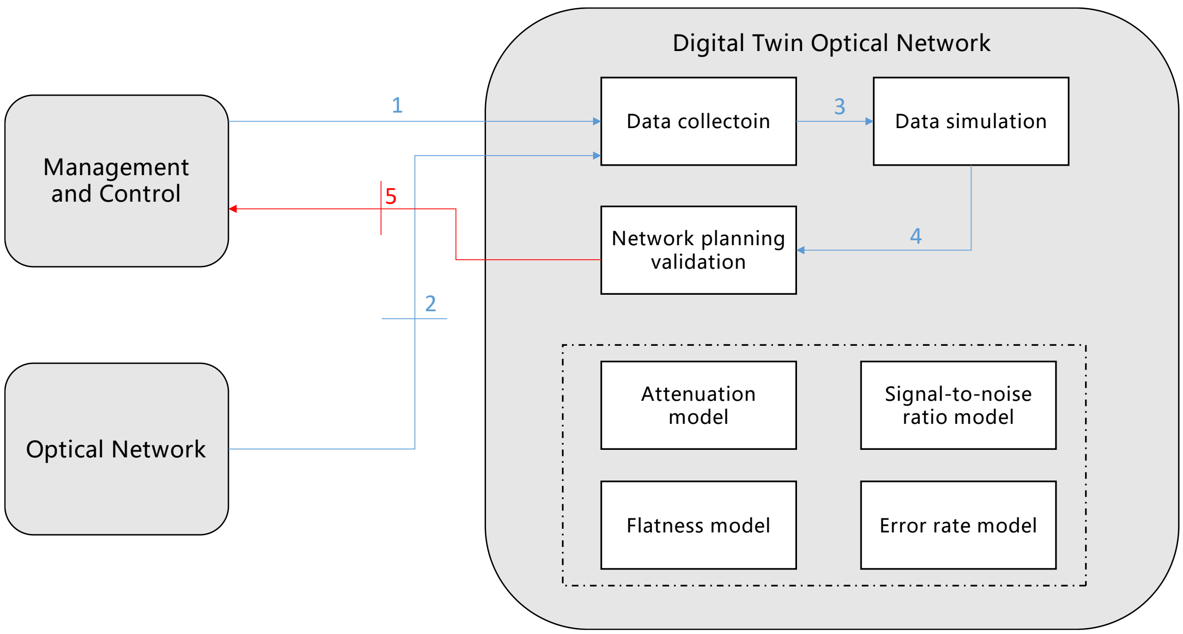

Figure 7 Interaction with network planning and simulation

The detailed description of each step in **Error! Reference source not found.**Figure 7 is as follows:

Step 1: The digital twin optical network acquires the information of optical network products and performance requirements. The products information could be equipment types, board types and port types from MC system or resource management system. The performance requirements could be transmitter power, receiving sensitivity, overload optical power, central wavelength, extinction ratio. The fibre information including fibre type, attenuation, dispersion, fibre length, fibre connectors should be available.

The digital twin optical network can get network requirements from the planning and design staff (i.e. network scale, network capacity, performance requirements, topology, node type, node quantity, OSNR, line error rate, flatness, margin of attenuation redundancy in optical cable routes, etc.).

Step 2: The digital twin optical network can get network performance and component performance characteristics from MC system.

Step 3: The data simulation function can simulate and calculate the network performance to meet the network requirements (OSNR, line error rate, flatness, margin of attenuation redundancy). If the network performance can not meet the requirements, it should propose to adjust equipment types or performance for optimal suggestion. The simulated network plan scheme should meet the network requirements.

Step 4: The network planning validation function outputs the network planning and design scheme that has been simulated and verified, including network scheme and equipment configuration scheme.

Step 5: The planning and design staff can check the plan scheme with the MC system, keeping consistency between planning scheme and actual network deployment. Engineering deployment staff can directly carry out engineering implementation according to the planning scheme.

3. Use Case driven requirements

- Input data requirements

a) The product information and performance requirements of optical network equipment include: optical network product types, board types, port types, interface performance requirements, optical equipment performance requirements.

b) Fibre resource information includes: fibre types, fibre attenuation, fibre dispersion, fibre performance requirements.

c) Network planning requirements include networking information (networking topology, node type, number of nodes), network equipment information (such as equipment types, board model, port type, etc.), and input fibre resource information (such as fibre length, fibre section, type, number of connectors, attenuation, etc.)

Table 9 Input of data collection

Data		**Description**
Equipment data	Equipment types	All kinds of equipment types can be available for network deployment.
	Board types	All kinds of board types can be available for network service deployment.
	Port types	All kinds of port types can be available for network service deployment.

	Ports data	Performance data of ports, including port rate.
	Performance of optical components	Performance and component performance characteristics of optical components including transmitter power, receiving sensitivity, overload optical power, central wave-length, BER
Fibre data	Fibre types	G.652, G.653, G.654E, etc.
	Attenuation	The attenuation at specific wavelength λ between two cross sections 1 and 2
	Dispersion	The dispersion of different fibre
	Number of fibre segments	Number of fibre segments of each optical channel.
	Cable length	The cable length between two adjacent optical cable splice closure.
Requirements of network planning	Topology	Topology represents link and subnetwork (switching) resources. These resources may be abstract or supported by software and hardware implementations.
	Node type	Core site, aggregation site, access site
	Internal fibre connection	Fibre connections among boards within each node.
	External fibre connection	Fibre connections between nodes.

- Processing requirements

a) The digital twin optical network should support configuration synchronizing or collecting board, port and performance information of various optical network equipment from the MC system and network equipment product specifications, in order to conduct sufficient and reliable simulation verification.

b) The digital twin optical network should support synchronizing or collecting various types of fibre performance requirements and fibre data information from the network resource system, providing a data foundation for network planning and design.

c) The digital twin optical network should support data processing input from the optical network or MC System, such as labeling, classification, cleaning, etc., to improve efficiency for simulation.

d) The digital twin optical network should support AI application, which can simulate and calculate network performance parameters (such as receiving power and transmitter power, OSNR, line error rate, flatness, etc.) based on network equipment configured by planning and design personnel and input network parameters (such as fibre distance, model, number of joints, attenuation, etc.), and can provide optimization suggestions for problematic network equipment or fibre optic cable sections, and output the optimal solution.

e) The digital twin optical network should support network planning and design scheme verified with the optical network, automatically forming configuration scheme, generating network deployment scheme, and synchronize the configuration scheme with the MC system to keep consistency between planning scheme and the optical networking configuration.

Table 10 Output of network planning validation

Data		**Description**
Equipment data of planning scheme	Equipment types	The suitable equipment types for network deployment.
	Board types	The suitable board types for network service deployment.
	Port types	The suitable port types for network service deployment.
	Ports data	The suitable performance of ports for network service deployment, including port rate.
	Performance of optical components	The suitable Performance of optical components for network service deployment, including transmitter power, receiving sensitivity, overload optical power, central wavelength, BER
Network planning scheme	Topology	The topology meets the planning requirements, which represents link and sub-network (switching) resources. These resources may be abstract or supported by software and hardware implementations.
	Node type	The node types meet the planning requirements.
	Internal fibre connection	Fibre connections within each node meet the planning requirements.
	External fibre connection	Fibre connections between nodes meet the planning requirements.
Performance simulation result	Receiving power and transmitter power	Optical power of each port.
	OSNR	Simulated OSNR of each cable segment
	Line error rate	Simulated line error rate
	Flatness	Simulated flatness
	Attenuation redundancy	Margin of attenuation redundancy in optical cable routes

- Interface and function requirements

a) Get topology information.

b) Get NE information.

c) Get performance data.

d) Get component performance characteristics.

e) Get configuration data.

f) Set configuration data.

3.5 Use Case #5: Cutover scheduling and risk assessment

1. Overview

A "cutover" operation means a change to the topology, capacity, equipment, and services in an optical network during a defined maintenance window. Optical network cutover is used to meet development requirements of redeploying or configuring optical network physical resources such as equipment, cables, facilities, services and user data. Optical network cutover is an important operation for network construction, network expansion and network optimization. This operation often causes service interruptions or service switchover. Cutover involves a wide range of objects, these objects are connected to each other and affect each other. So cutover is not a local isolated event. For traditional optical network cutover, it is difficult to reasonably organize and arrange multiple cutovers to avoid conflicts and improve efficiency. It is also difficult to accurately assess the disadvantage effects of the cutover process in advance. To improve cutover efficiency and avoid the conflict, it is desirable to evaluate and organize the cutover schedule.

With intelligent calculation, simulation and verification, the digital twin optical network solves the scheduling of multiple cutover jobs across multi-domain and multi-layer, disciplines to reduce the risk of mutual impact. The digital twin optical network can simulate the cutover, validate the schedule plan and assess the cutover risk.

2. Interaction with enhanced network operations

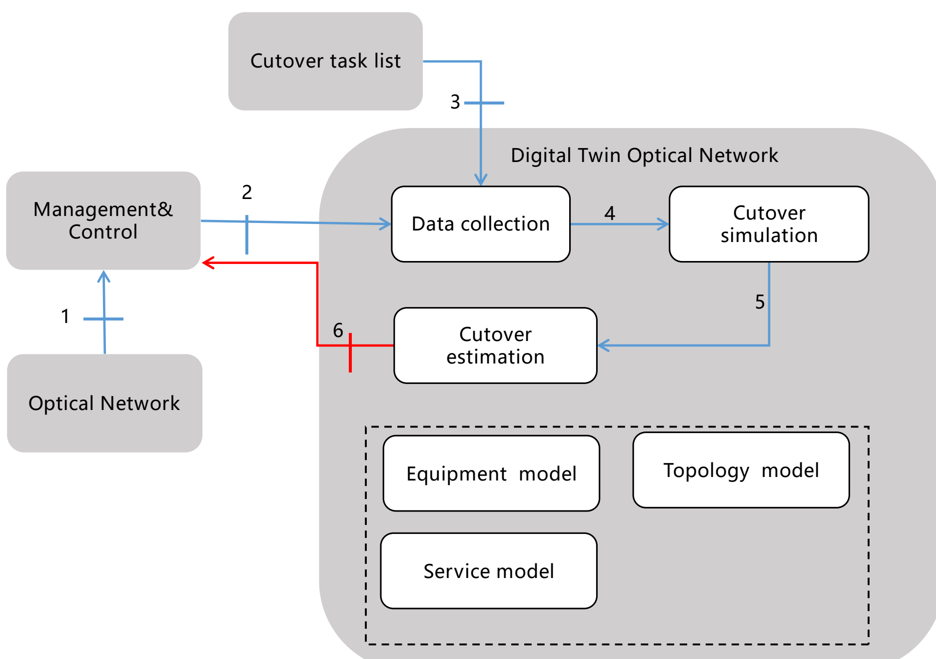

Figure 8 Interaction with cutover scheduling and risk assessment

The detailed description of each step in **Error! Reference source not found.**Figure 8 is as follows:

Step 1: MC system collects necessary data from optical network by a collection method.

Step 2: MC system provides some data as shown in Table 11 (e.g., topology information, NE information, service information) as input of the Digital Twin Optical Network.

Step 3: Network maintenance personnel input cutover tasks list within a certain period as one of the inputs to the digital twin optical network. It includes the objects involved in cutovers, such as equipment, optical cables, service of the optical network and the start and end time periods of the intended deployment.

Step 4: The cutover simulation function intelligently simulates multiple cutover tasks (during the start and end time periods) in the future planning period based on the multi-layer, multi-region, service association and cutover rules of the network where the cutover object is located, so as to achieve optimal scheduling plan, reduce mutual influence, and improve cutover efficiency. The intelligent scheduling plan could be available.

Step 5: The cutover simulation function simulates the cutover operation process and scheduling plan according to the cutover task list, and then analyzes the possible risk of service cutover. The objects (equipment, lines, or data) and steps (the operation sequence of the cutover) and the scheduling plan are simulated to find the damage to the service. The maintenance staff could evaluate the feasibility and security of the cutover solution and could optimize the solution.

Step 6: The cutover estimation function generates a risk assessment report and scheduling plan after verification, and outputs the plan to the MC system or the maintenance staff. The risk assessment report must contain information about the service damage caused by each cutover task during specific operation steps. The maintenance staff evaluate the feasibility of the solution based on the risk assessment report and decide whether to execute or optimize the solution.

3. Use Case driven requirements

- Input data requirements

a) Requires collection of topology, NE information, and optical cable (ID, length).

b) Requires collection of service information.

c) The task ID, cutover operation object, scheduled cutover time and period, and cutover scheduling rules of the multi-cutover task.

Table 11 Input of data collection

Data		**Description**
Topology	Topology ID	Topology represents link and subnetwork (switching) resources. These resources may be abstract or supported by software and hardware implementations. The topology identifier is unique in the context of some scope which could be global.

	Number of fibre segments	Number of fibre segments of each optical channel.
	Fibre types	G.652, G.653, G.654E, etc.
	Fibre length	The cable length between two adjacent optical cable splice closure.
NE	NE id	The identifier of network element.
	Board id	The board may plug into equipment. The Board id is unique in the context of some scope.
	Port id	The port can perform the termination and adaptation functions of one or more transport layers. It supports all transport protocols including circuit and packet forms. The port identifier is unique in the context of some scope.
Service information	Service routing, connection and service quality.	
Cutover task information	Task id	The task ID of the multi-cutover task
	Cutover object	The objects involved in the cutover task, i.e. NE, board, port, fibre segment and service.
	Cutover steps	The procedure specified in the cutover scheme.
	Cutover time period	The period of cutover from starting time to stop time.
	Cutover rules	The rules to avoid cutover risk.

- Processing requirements

a) The digital twin optical network shall support collection of resource information such as boards, ports, links and service connection information of various optical network equipment from the MC system.

b) The digital twin optical network should support collection of cutover task information from the MC system or other external systems (such as the task ticketing system), including the object of the cutover task (such as equipment, line, or service), cutover time, and cutover rules).

c) The digital twin optical network should support the risk analysis of AI to the cutover scheme. The digital twin optical network can propose the cutover steps from the scheme, simulate and verify the cutover steps, find the impact on service damage, and verify the integrity and executability of the steps.

d) The digital twin optical network should support analyzing of the cutover schedule and correlate multiple cutover tasks in the same time period and intelligently schedule different cutover tasks according to the safest and most efficient strategy.

e) The digital twin optical network should support generation and verification of cutover schedule and send the scheme to MC system.

f) The digital twin optical network should analysis and verify the cutover risk service damage, and generate early warning for the cutover service.

- Output data requirements

a) The cutover schedule should ensure the scientific planning and safety.

b) Network cutover solution contains risk and damage information caused to the service.

Table 12 Output of cutover estimation

Data		**Description**
Cutover schedule	Cutover tasks	The multi-task list scheduled by the digital twin optical network.
	Scheduled time period	The time period scheduled by the digital twin optical network.
Cutover scheme and risk	Cutover objects	The objects involved in the cutover task, i.e. NE, board, port, fibre segment and service.
	Cutover steps and influence	Cutover steps and the risk of mutual impact.
	Cutover scheduling impact	Information about the damage caused by the simultaneous cutover of multiple cutover tasks in the schedule.

- Interface and function requirements

a) Get topology information.

b) Get NE information.

c) Get service information.

d) Get cutover task list.

e) Set cutover schedule.

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5 Glossary

ASON	Automatically Switched Optical Network
BER	Bit Error Ratio
CC	Connection Controller
DT	Digital Twins
EMS	Element Management System
FCAPS	Fault, Configuration, Accounting, Performance, and Security Management
FEC	Forward Error Correction
LRM	Link Resource Manager
MC	Management & Control
NCC	Network Call Controller
NMS	Network Management System
NE	Network Element
OA	Optical Amplifier
OCh	Optical Channel
ODU	Optical Data Unit
OSNR	Optical Signal-to-Noise Ratio
OTDR	Optical Time Domain Reflectometer
OTU	Optical Transport Unit
PMD	Polarization Mode Dispersion
RC	Routing Controller
ROADM	Reconfigurable Optical Add/Drop Multiplexer
SDN	Software Defined Network
SLA	Service Level Agreement
SNMP	Simple Network Management Protocol
VOA	Variable Optical Attenuator
WSS	Wavelength Selective Switch