New ICT infrastructure and reference architecture to support Operations in future PI Logistics NETworks

D2.5 PI networking, routing, shipping and encapsulation layer algorithms and services Final

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Glossary of terms and abbreviations used

Abbreviation / Term	**Description**
ERP	*Enterprise Resource Planning System*
IP	*Internet Protocol*
LES	*Logistics Execution System*
NOLI	*New Open Logistics Interconnection*
OLI	*Open Logistics Interconnection*
PI	*Physical Internet*
PoC	*Proof of Concept*
RIP	*Routing Information Protocol*
WMS	*Warehouse Management System*

EXECUTIVE SUMMARY

Th r port pr s nts th Physical Int rn t (PI) four cor s rvic s, nam ly th Shipping, ncapsulation, Routing and N tworking. Th s rvic s hav n d sign d to align with th OLI/NOLI (and ICON T) lay rs na ling a standardis d approach to th PI impl m ntation. Th G n ric Physical Int rn t Cas Study (GPICS) has also n tak n into consid ration, as it off rs th und rlying PI ontology with which th PI S rvic s hav n d sign d to int ract. Th ontology of PI Links, Nod s and S rvic s in its g n ric form is inh rit d from th GPICS and xt nsions ar consid r d as ach s rvic is xamin d into furth r d tail. Th s rvic s ar d sign d to account for various usin ss typ s wh r various us cas s aris . Th s qu nc of communications of th PI S rvic s d sign has n consid r d for ach us cas , aiming to na l th d v lopm nt of modular and ro ust s rvic s. Th various applications cont xts of th PI hav also n tak n into account, drawing on th adaptations of th four cor s rvic s to th ICON T Living La r quir m nts.

Th d scription of th cor PI S rvic s, uilds on th s cond v rsion of this r port and provid s th final and compl t s rvic d sign.

Th shipping s rvic has an ov rarching manag r rol and can divid d into: d sign; initialization; arrival at PI nod ; and r al tim updat modul s. Th function of th first two modul s is associat d with th r qu st of shipm nt through th and th d v lopm nt of th PI Ord r. Th Arrival at PI nod modul handl s th s qu ntial hops of PI contain rs in th ir rout to th ir d stination, whil th r al tim updat s modul , communications with th IoT platform and coll cts data to track th p rformanc of th PI shipm nt against its contractual o ligations.

Th ncapsulation s rvic inv stigat s th in packing algorithm as w ll as algorithms for ov rcoming its computational compl xity. Th ncapsulation s rvic addr ss s th ncapsulation of cargo into PI contain rs, into H contain rs into T contain rs into PI Mov rs/M ans. It off rs a g n ric tool for improving op rational ffici ncy and d cision making at PI Hu s. Variations of th g n ric mod l ar d scri d that can also utilis d for ffici nt Comm rc ncapsulation.

Th n tworking s rvic primary function is n twork discov ry, in ord r to provid a standardis d and compl t r pr s ntation of th PI for furth r d cision making. Using th GPICS as a guid lin , an nhanc d data structur is propos d r aking down th PI n twork information into static and dynamic data for PI Links, PI Hu s and PI Mov rs. Furth rmor , consid ring th ICON T Living La s, s v ral n twork r pr s ntation approach s ar consid r d focusing at varying n twork aggr gations. A guid lin for n tworking s rvic impl m ntation into diff r nt cont xts is also provid d.

Th routing s rvic inv stigat s th computational compl xity and h uristics for improving th solution tim for g n ric and sp cialis d PI routing pro l ms. Th p rformanc of m thods utilising an int gration of optimisation and machin l arning m ans ar discuss d in d tail, for proposing an PI.

All S rvic s pr s nt d in this r port hav n int grat d with th PoC Platform. Th communication tw n th PoC has n impl m nt d y using ith r dir ct (S rvic X to S rvic Y) or indir ct (S rvic X – Simulation – S rvic Y) Application Programming Int rfac s (API).

1 INTRODUCTION

Goods and products are transported from one location to another where they will become more useful and valuable. There are several stages in the development of a product, starting from one or more raw materials, going through several processing and assembly stages, before it finally reaches a retail store, and is purchased by the final customer. In economies, agglomeration contributes to the expansion of supply chains as processes tend to be increasingly specialised. Additionally, products are becoming increasingly varied and complex emphasizing the need for supply chain flexibility.

For most developed countries, economic productivity (typically expressed through the Gross Domestic Product) is found to be directly associated to the amount of goods movement. Establishing an efficient system for moving goods, is an essential milestone for commerce while at the same time extracting high re-capacity from legacy infrastructure such as railways, and motorways. Furthermore, with sustainability becoming an increasing concern, logistical solutions in transport become more relevant, aiming to satisfy transportation demand in an environmentally friendly manner. Although methods and technologies for planning and executing transport and logistics have improved with time, the main principles and inefficiencies still apply today.

Performance of freight transportation is one of the crucial elements for the sustainability of logistics and supply chain. The costs for the freight transportation can reach up to 60% of the total logistics costs for shippers, Collignon (2016) and inefficiencies in transportation costs can be characterized by economic, social and environmental inefficiencies and unsustainability. Despite efforts by transport companies, the frequency of empty trips remains high and average truck fill rate is low. Overall, according to Eurostat (2017), at total transport level, most trucks in Europe fell in the range between 15 % and 30 % empty journeys. Moreover, freight transportation (in developed countries) is responsible for nearly 15% of greenhouse gas emissions. This ratio has been increasing despite ambitious reduction targets. Improved transportation efficiency is therefore an important objective of the Physical Internet and it aims to reduce logistics costs by building on concepts from Digital Internet that enabled the development of global system of the data transport across heterogeneous networks exploiting standard datagrams and protocols.

The Physical Internet (PI) promises to revolutionise how transport and logistics is practiced, and to improve on critical variables such as cost, utilisation rates, and emissions through improved multi-modal integration and open accessibility to static and mobile infrastructure. The core constraints, objectives and business processes involved in planning, coordinating and executing the transport of goods from origin to destination remain largely unaltered in a PI approach. What changes under the PI is the standardisation and interoperability of transport, logistics systems and processes. For these features of the PI to materialise, several information and decision support systems as well as standardisation and integration services require to be introduced. In this report we discuss the following transport and logistics processes under a PI approach:

- *Encapsulation*: Standardises the packaging process of cargo and goods that are consolidated/deconsolidated into π-containers for transportation via the PI. It is also responsible for the consolidation/deconsolidation of π-containers into π-movers.
- *Shipping*: Specifies what has to be transported as well as the transportation process conditions and constraints. It is responsible to make appropriate adjustments to the shipping instructions to ensure compliance.

- *Networking*: N tworking d fin s th int rconn ct d infrastructur of availa l proc ssing, storag and transporting faciliti s (transport s rvic s, t rminals, distri ution c ntr s, war hous s) through which th goods will transport d from th ir origins (manufacturing, distri ution and oth r locations) towards th ir custom r(s) locations.
- *Routing*: Routing is a proc ss that cr at s a plan that d scri s th stag y stag d tail d visiting and usag of n tworking nod s and links from origin to d stination.

Th a ov proc ss s:

- Hav diff r nt planning horizons: long m dium and short t rm
- Tak plac at diff r nt stag s, hav diff r nt durations and may r p at d in th spac of a singl transport proc ss.
- Ar support d y diff r nt IT syst ms (RP, Transportation Planning, war housing manag m nt, and oth rs).

ach proc ss r c iv s r quir m nts/constraints a out on of th parti s involv d in th transport/logistics chain and mak s d cisions which ar furth r communicat d to and int rpr t d y oth r parti s. In th cont xt of PI th s proc ss s ar furth r distri ut d and d c ntralis d, sinc PI is a n twork of n tworks and ach of th int rconn ct d n tworks may own d/controll d y diff r nt actors.

1.1 Changes since previous versions of the report

V rsion 1 of this d liv ra l provid d a succinct and a stract d finition of th shipping, n tworking and routing proc ss s und r PI. With analysis of r al transport proc ss s from th Proj ct's Living La s and th d v lopm nt of a G n ralis d PI mod l (GPICs) in Work Packag 1, d scription of th PI proc ss s was furth r la orat d.

V rsion 2 contain d a mor xt nsiv d scription of PI proc ss s as w ll as an arly prototyp of a rout plann r und r PI. Th ncapsulation PI proc ss that r quir s sp cialis d loading units (PI-contain rs) and oth r suita l handling and transporting quipm nt was d scri d in d tail. Protocols int grat d with Op rations R s arch algorithms for und rtaking th ncapsulation proc ss w r propos d. information asp cts of ncapsulation hav n discuss d in th first v rsion of this r port and also in d liv ra l s D2.1 PI R f r nc Archit ctur v1 and D1.11 PI Protocol Stack and na ling n tworking t chnologi s v2.

In th curr nt and final v rsion of th docum nt, furth r cas studi s of PI shipping n tworking and routing ar pr s nt d with r f r nc to th Proj ct's Living La s and furth r shipping, n tworking and routing d monstrators ar provid d. Sp cific cas studi s d riv d from th Living La s provid information for th la oration of th PI proc ss s.

1.2 Processes, Algorithms and services for PI shipping, encapsulation networking and routing

In this r port w analys th proc ss s of transportation und r PI approach. Th automation of such proc ss s r quir s suita l IT syst ms and s rvic s. Such s rvic s ar softwar impl m ntations of planning, routing tc. d cision support algorithms. Th r ar alr ady many typ s of syst ms (Transport Manag m nt Syst ms-TMS, nt rpris R sourc Planning Syst ms- RP, War hous Manag m nt Syst ms-WMS and oth rs) that provid such s rvic s to transportation us rs and p rform rs. In this r port w att mpt to analys th proc ss s from a PI p rsp ctiv , to sta lish wh r n w typ s of d cisions n d to support d, n w information s rvic s to support such d cisions, and n w nt rpris syst ms to d v lop d or curr nt on s to ov rhaul d.

Propos d PI S rvic s utilis math matical programming for optimising d cision making for th g n ric shipm nt of cargo through th PI, as w ll as for various Us Cas s that aris in th transport proc ss. An algorithmic approach and variations of optimisation pro l ms (chang s in varia l s or constraints) ar discuss d w r appropriat . Furth r algorithms ar sp cifi d as PI mod ls ar appli d to th Proj ct's Living La sc narios, and prototyp IT s rvic s impl m nting such algorithms, ar nvisag d in th cours of th Proj ct.

1.3 Deliverable Overview and Report Structure

Th r port consists of th following s ctions. S ction 2 provid s a ackground ov rvi w of th main actors and activiti s involv d in th transport (nd to nd) proc ss, th d scription of th OLI/NOLI lay rs, th GPICS r pr s ntation and data structur . Using th int rconn ctions mad and ackground mat rial pr s nt d in S ction 2, th r port th n is d compos d into its parts: shipping, n tworking and routing, that ar xt nsiv ly discuss d in s ctions 3-6 r sp ctiv ly. For ach PI S rvic , th main consid rations for th d v lopm nt of th s rvic ar discuss d and analys d for proposing a g n ric protocol d sign. ach Chapt r th n looks furth r into th d tail of th compon nts of ach protocol for addr ssing oth th cor PI functionality, ut also for addr ssing additional Living La inspir d us cas s. xampl s of PI S rvic impl m ntation ar also provid d illustrating S rvic functionality. In s ction 7 a summary of th work und rtak n and concluding r marks ar mad that focus on th compl xity that can handl d y th propos d PI s rvic s and th ir int rcommunication. S ction 8 contains r f r nc r sourc s.

2 BACKGROUND READING AND SUMMARY OF RELEVANT ICONET WORK

This section attempts to connect the various ICONET services to supply chain and logistics concepts and to align development work across the ICONET project and the literature in general. The Chapter builds on work presented in the previous two deliverables D2.3 and D2.4 on PI Services, as well as D1.8 on GPICS and D2.2 on the PI Reference Architecture. Section 2.1 covers the transport process in practice, and attempts to make associations to the digital internet in order to establish the physical internet's functionality requirements. Section 2.2 focuses on the OLI, NOLI layers and connects the notions to ICONET layers and the architecture presented in D2.2, that is later used as the basis for developing the PI Services protocols. Finally, Section 2.3, focuses on the GPICS and the proposed generic network representation, that PI Services build on.

2.1 Overview of the Transport Process

2.1.1 Main actors and roles in Transport and Logistics

Logistics and transport involve the coordinating effort of several organisations, each of them focusing on a different part of the logistics and transportation process. A supply chain includes not only the manufacturer and the suppliers, but also transporters, warehouses, retailers, and even customers themselves. Although this may include organisations that have only an indirect role such as for example banks and insurance companies, we focus only on those organisational roles that are directly involved in the transport and logistics process.

Their involvement as stakeholders in the transport and logistics processes can be due to them owning (initially or ultimately- i.e. as sellers and buyers) the goods that are transported, the equipment and other resources by which the goods will be processed and transported, or because they are coordinators of the different processes and activities involved. We define different *roles* for actors participating in transport. It is possible for the same organisation to assume multiple roles in the process. So an organisation (or more accurately different legal entities within it) can at the same time be all seller and buyer, freight forwarder and carrier.

The functioning of a supply chain involves three key flows – information, product and funds as illustrated in Figure 2.1. The goal when designing a supply chain is to structure the three flows in a way that meets customer needs in a cost effective manner (Chopra, 2019).

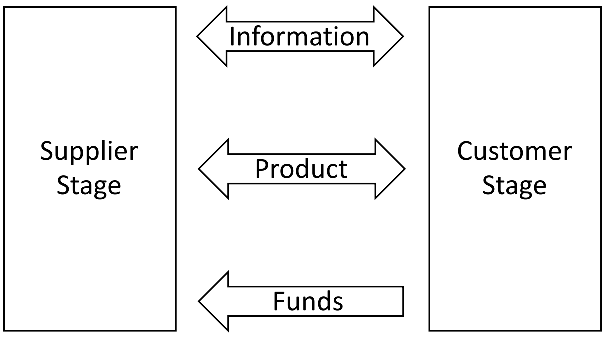


Figure 2.1: The three flows in a supply chain

Of cours , und r th PI approach pr vious c ntralis d activiti s may com d volv d amongst multipl parti s. It is mor lik ly that multipl organisations may r sponsi l for ach of th following rol s, for a singl transport act, rath r than th r v rs , i. . th sam organisation assuming multipl rol s. For instanc , in many supply/transport chains, th s ll r may utilis th s rvic s of a singl (or small group) of carri rs und r a singl contract. Und r PI, wh r it is mor lik ly that diff r nt carri rs may us d for th diff r nt l gs of transport, such carri rs may not in dir ct contract with th s ll r (or v n und r su contract with th s ll r's main carri rs).

With all th a ov tak n into account, th following rol s ar d fin d that will tak n y actors participating in th shipping, n tworking and routing proc ss s discuss d in th following s ctions of th r port.

- Shipp r: Th organisation that initiat s th transport proc ss y su mitting a transport r qu st to th fr ight forward r.
- Custom r: Th organisation that will r c iv th transport d goods.
- Fr ight Forward r: Th organisation that plans and coordinat s/ov rs s th ov rall transportation proc ss.
- Carri r: Th organisation r sponsi l for th physical mov m nt of th goods.
- Logistics S rvic Provid r: Th organisation that provid s s rvic s r lat d to th transport of goods such as storag .
- Int rmodal t rminal (hu): Th organisation that provid s th s rvic s to r -rout or r -load goods onto diff r nt transport m ans, as th y ar mov d towards th ir final d stination, for xampl y trans-shipping. Th hu can also provid oth r s rvic s, similar to thos of th Logistics S rvic Provid r. An int rmodal t rminal for instanc , loads and unloads contain rs and trail rs to and from rail wagons for mov m nt y rail and su s qu nt mov m nt y road.

2.1.2 Breakdown of processes for transporting goods via PI

Actors r quir to coordinat th ir activiti s to succ ssfully transport goods. As illustrat d in **Figure 2.2**, th proc ss s involv d ar summaris d low:

- Shipping instruction: Th transport proc ss initiation activity wh r a s ll r (shipp r) instructs a fr ight forward r to ship its goods via PI. Shipping instructions ar us d for instructing shipping conditions such as siz , volum , packaging, tc.
- *Network design and network selection:* This proc ss r quir s th tactical planning and d sign of th transportation n twork. This can th r sponsi ility of th shipp r organisation or th fr ight forward r. Du to th charact ristics of PI this will r quir colla oration (p ring agr m nts) tw n hu s (int rmodal t rminals), carri rs and oth r logistics s rvic provid rs. This is th r for a tactical (long t rm) proc ss. In contrast, n twork s l ction is th proc ss of choosing amongst alt rnativ n twork paths, as d on th shipping instruction. In n twork s l ction th fr ight forward r/transport plann r d cid (in association with, as d on th shipping instruction r c iv d, th path(s) through th PI that th cargo will follow to its d stination. This also includ s th d cision of how to split th cargo in multipl consignm nts that will forward d along multipl paths to th final d stination.
- *Transport route planning:* Planning th transport rout is also a colla orativ as d d cision wh r out of th possi l rout s through th s l ct d n twork, a suita l rout is s l ct d, as d on th charact ristics of th consignm nt and also on th stat of th n twork (curr nt and futur) at th tim of planning.

- *Transport Execution:* Transport x cution includ s th activiti s that physically mov cargo towards its d stination, possi ly via int rm diat st ps (l gs') and involving switching tw n diff r nt logistics quipm nt and additional activiti s that for xampl stor , undl or un undl cargo. Th ord r at which st ps ar follow d can pr -d fin d or a r sult of r -planning aft r th compl tion of ach st p.

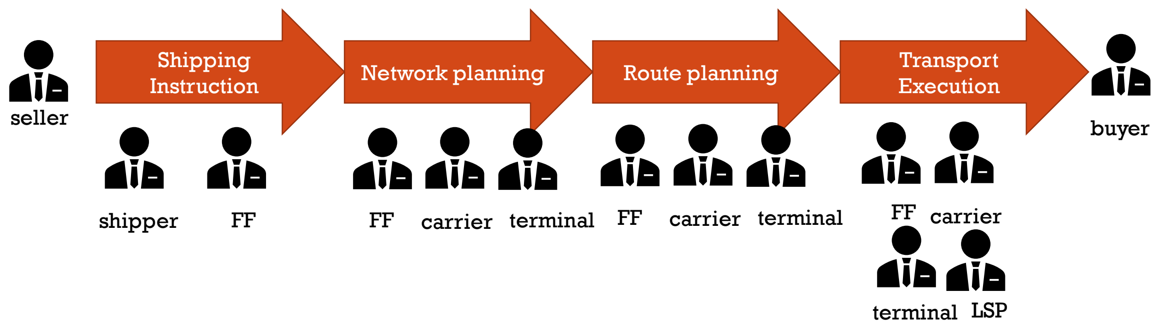


Figure 2.2: Visualising the steps of transporting via PI

2.2 The ICONET layers

A high-l v l d scription of th lay rs that th ICON T proj ct r li d upon as w ll as th ir association to th OLI and NOLI lay rs is pr s nt d in D2.2 – PI R f r nc Archit ctur . Th d liv ra l introduc s th ICON T lay rs in association to th PI S rvic s that ar d scri d into furth r d tail into this r port.

2.2.1 The ICONET Services

Th ICON T R f r nc mod l indicat s th r lationship tw n th OLI, NOLI and ICON T lay rs, as w ll as th ICON T s rvic s to us d for t chnical impl m ntation for th ICON T proj ct.

A Physical s rvic was d m d out of scop for furth r t chnical work, as it would r quir significant ffort to synchroniz physical actions with th corr sponding op rations d scri d in th PI conc pt and th Physical Lay r. Additionally, adoption of th s PI- as d physical actions would difficult at this curr nt stag .

Mor ov r, th functionaliti s and off rings of th Link lay r pr s nt d in a th or tical mann r a ov , ar v ry clos to th sp cifications off r d y th Shipping lay r, and as such, th d cision was mad to unify th s functionaliti s in a singl Shipping s rvic which in conjunction with oth r s rvic s, will provid m chanisms for ffici nt and r lia l shipping. As illustrat d in Figur 2.3, th s rvic s wh r th ICON T proj ct will focus to ncompass th majority of r l vant functionaliti s on ar th following:

- Shipping
- ncapsulation
- N tworking
- Routing
- Optimisation
- Logistics W

OSI Layer	OLI Layer	NOLI Layer	ICONET Layer	Resulting Service
Application	Logistics Web	Product	Logistics Web	Logistics Web
Presentation	Encapsulation	Container	Encapsulation	Encapsulation
Session	Shipping	Order	Order	Shipping
Transport		Transport	Transport	
Network	Routing	Network	Routing	Routing
	Network		Network	Network
Data Link	Link	Link	Link	-
Physical	Physical	Physical Handling	Physical	-

Figure 2.3: Representation of ICONET layers and services with respect to the OSI, OLI, and NOLI layers

2.3 GPICS components description

Th GPICS mod lling compon nts ar d sign d to allow th composition of a g n ric PI n twork trough standard mod lling l m nts. GPICS compon nts captur all ICON T lay rs, starting from th low aggr gation of infrastructur for th Physical and Links Lay rs. Through th appropriat configuration, th s l m nts r pr s nt diff r nt typ s of supply chain flows. Th structur of th g n ric mod l consists of th following main l m nts:

Table 2.1: Reference to ICONET D1.8

GPIC structure	
GPICS Container	Unit load manipulated, stored, moved and routed through the systems and infrastructures of the Physical Internet.
GPICS Node/Hub	Location specifically designed to carry out logistics and transport processes and activities on PI containers.
GPICS Transport	Moving element used to carry PI containers through the PI nodes/hubs.
GPICS Corridor	Connection between two PI Nodes/Hubs directly connected.
GPICS Route	Set of GPICS corridors which connect a GPICS Node origin and a GPICS Node destination.
GPICS Network	Set of containers, nodes, movers/transport, corridors, and routes.
GPICS Roles	Actors/Agents involved in the operation of the PI Network.

ach of thos cor GPIC compon nts, can furth r su divid d into f atur s and prop rti s that d scri it. For xampl , GPICS Contain r information includ :

- Contain r ID

- Origin and D stination IDs
- S nd r and R c iv r IDs
- D liv ry tim window
- GPS coordinat s/ location.

Similarly, for ach PI hu a classification in t rms of functionality is appli d into Gat way, Sourc , Switch, tc. For ach of thos functionaliti s, information on th infrastructur constrain d throughput is also stor d. Furth rmor , th GPICS ring tog th r th r quir m nts of th four ICON T Living La s. Taking into account th sp cificiti s of ach of th m, th r pr s ntation and d scription ar mad through th cr ation of a hi rarchical structur and th d p nd ncy of th GPICS Hu s. Mor sp cifically, a thr -l v l structur (du to th maximum l v ls r quir d y LL) of HUBS has n d fin d. Th r for , wh n d fining, ach G n ric HUB longs to L1, L2 or L3, in th instantiation proc ss for a sp cific g n ric d finition of a cas study. Th d p nd ncy is as d on a simpl rul : a L2 Hu d p nds dir ctly on a L1 Hu and a L3 Hu d p nds dir ctly on a L2 Hu . Indir ctly, a L3 Hu d p nds on th corr sponding L1 Hu as illustrat d in Figur 2.4.

Th r for , for PI Hu s th information maintain d ar :

- Nod ID
- L v l
- Dir ctly conn ct d nod s
- Functions and th ir throughput
- GPS coordinat s.

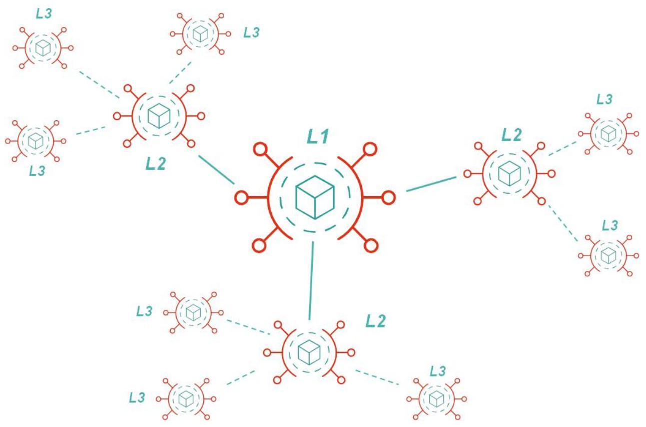


Figure 2.4: GPICS three level structure of PI Hubs (ICONET D1.8)

As for v ry graph, in th PI as w ll, information on th p rformanc of Links ar ss ntial for na ling th ility to mov ffici ntly through a n twork. According to graph th ory, n twork links can associat d to on or mor w ights that ar in ss nc link prop rti s. W ights can d p nd on static infrastructur prop rti s, as for xampl , th throughput of a road Link is associat d (among oth r factors) to th num r of lan s availa l and th typ of road link (.g. local or motorway). Link w ights can also associat d to dynamic link prop rti s such as trav l tim , that d p nd on th amount of traffic and cong stion l v ls on th link.

In th PI cont xt, to p rform th transport of cargo from an origin to a d stination, impli s that a transport tw n th s two PI Hu s is pot ntially possi l . To mak a transport r ality, this Link must configur d in at l ast on GPICS rout with at l ast on GPICS Mov /Transport, it must configur d in that rout and with param tris d stops in thos two GPICS Hu s. Th asic information that d fin s a GPICS Link is th following:

- Link ID
- Starting and nding Nod IDs
- Typ
- Capacity
- Cong stion
- Transit tim

A s qu nc of links forms a rout . In th PI, PI contain rs ar typically r qu st d to follow a s qu nc of mov m nts, wh r th origin of th first mov m nt is th contain r's origin and th d stination of th last mov m nt is th contain r's d stination. A GPICS rout is inh rit d as a prop rty of GPICS Transport or Mov rs, that r pr s nts th m ans of transport us d to carry contain rs through th n twork. A PI Mov r is r sponsi l for carrying a contain r for on or mor links or for th ntir rout . It is worth noting that a GPICS Rout can form of a singl link if such an option is availa l and it is found to optimal, or alt rnativ ly form as a s qu nc of links that r quir s ypassing PI Hu s as illustrat d in Figur 2.5. GPICS Mov rs do not n c ssarily follow th sam rout , and th r for th indir ct rout can fulfill d ith r y a singl or s v ral Mov rs. Th r for , similar to th GPICS Link information, it is ss ntial to maintain information of GPICS Mov rs, as in transport and logistics, th ffici ncy of transporting cargo tw n two nod s is ff ct d y th s rvic provid d y th Mov rs.

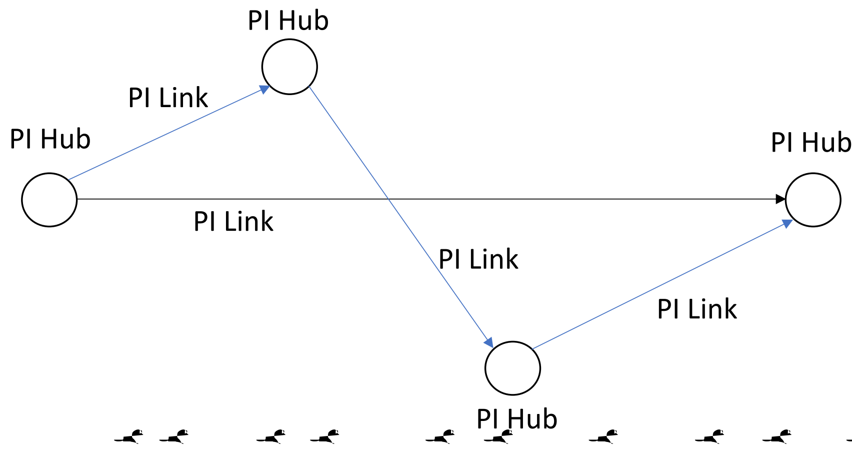


Figure 2.5: Direct and indirect PI Container Routes

Asid th information r lat d to th op rational ffici ncy asp ct, Mov rs, ing th handl rs of PI contain rs ar also classifi d in t rms of functionality, similar to PI Nod s. Functionality information na l th filt ring of PI Mov rs, such as contain r transit r quir m nts ar m t. Th asic information for GPICS Mov rs is:

- Mov r ID
- Typ
- Path ID
- S rvic Fr qu ncy
- S rvic Functionality
- Capacity
- Fill Rat

2.4 PI Architecture

2.4.1 Generic PI

Th GPICS classification of compon nts and th ir prop rti s do s a gr at d al, in na ling th mapping of PI functionality r quir d for r alising cargo s transport. ICON T n tworking, routing, shipping and ncapsulation s rvic s ar th r for d sign d to manag and mak d cisions on th op ration of ach of thos n twork compon nts. Following, th ICON T Lay rs from top-down, and utilising th GPICS compon nt d finitions, th Logistics W Lay r, is r sponsi l for r tri ving from th s nd r information on:

- Origin and D stination IDs
- S nd r and R c iv r IDs
- D liv ry tim window.

Th ncapsulation lay r is th r sponsi l for fitting th cargo to transport d into on or mor PI Contain r as ffici ntly as possi l , storing th ir ID and na ling th ir GPS tracking. This forms an ord r to mov a PI Contain r from a sp cific Origin to a sp cific D stination within a sp cific tim fram . Th Shipping lay r is r sponsi l for assigning Transport/ Mov rs to an Ord r. To achi v this, it communicat s th PI Origin and D stination nod information to th Routing and N tworking s rvic s, and at fr qu nt int rvals ch cks if th routing instructions provid d y th Routing and N tworking s rvic s d viat from th PI Ord r r quir m nts. This can du to unc rtainty or chang s in th stat of th N twork. If that is th cas , th Shipping s rvic s initiat s a r qu st to updat th routing instructions for th sp cific at a high r urg ncy.

Th N tworking s rvic onc it has r c iv d th Origin and D stination ID's as w ll as th d liv ry tim window information, accumulat s th static and dynamic information on PI Nod s, PI Rout s and PI Mov rs availa l for fulfilling th PI Ord r. In doing so th n tworking s rvic filt rs out th n twork compon nts and s rvic s that do not satisfy th sp cific ord rs xplicit or implicit r quir m nts. xplicit r quir m nts includ for xampl cargo r frig ration, or transport mod sp cifications, whil implicit r quir m nt is for xampl r sp cting th ord r d liv ry tim window. Th n tworking s rvic , that also coll cts up to dat information on th n twork status, oth for infrastructur and s rvic s, communicat s it to th routing s rvic , that is r sponsi l for id ntifying optimal routing instructions for ach PI contain r.

Additional, to this cor functionality of th PI, th r ar add-on functionaliti s and d cision making tools, that na l th PI's ffici nt op ration that form part of th PI cor s rvic s. For xampl , an additional function of th routing s rvic in small n tworks is to d t rmin th routing of th PI mov rs, asid th routing of th PI contain rs.

D p nding on th capa ility and th information availa l to na l nhanc d d cision making, th PI proc ss can vary. As illustrat d in Figur 2.6, th PI proc ss propos d y Sarraj (2013) starts with ncapsulation and routing for r nt ring th r p titiv s gm nt for transporting cargo through th PI n twork hops. Wh n cargo has arriv d at th d stination, th contain r is unload d and th loop t rminat s. In contrast, if liv n twork status is consid r d in th d sign, only ncapsulation stag is und rtak n at initiation, and th r p titiv s gm nt starts with th routing id ntification. Th r for , as a PI contain r containing cargo, arriv s at a PI Hu , th rout to th d stination r quir s to r - valuat d with th most r c nt n twork information, as th n twork status might hav chang s and th r is a mor ffici nt rout to th d stination.

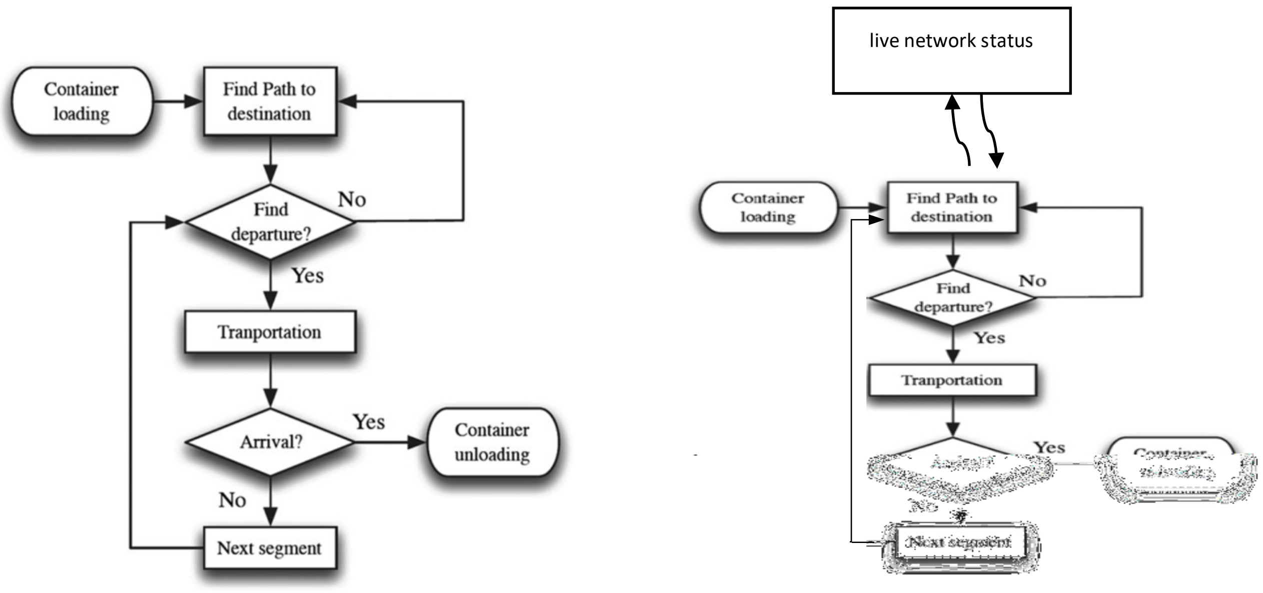


Figure 2.6: Transport process variations in the PI design (based on Sharraj et al., 2014)

2.4.2 PI business specific processes

Th PI n twork op ration is highly compl x, and ro ust functionality is r quir d to addr ss th varia ility in op rational r quir m nts as w ll as t chnical capa ility. Th following chapt rs of this r port look furth r into d tail in Shipping, ncapsulation, N tworking and Routing s rvic s, and th ir protocols that handl PI compl xity.

GPICS and ICON T lay rs ar us d as a guid lin in addr ssing th S rvic s r quir m nts throughout th r maind r of this r port. In an ffort to untangl PI compl xity, r f r nc s ar mad to th impl m ntation of th four s rvic s to ICON T living la s (LLs), and st-practic r comm ndations ar mad for adapting or xt nding th PI S rvic s pr s nt d as r quir d for th ir succ ssful d ploym nt.

Th four cor s rvic s hav   n co r at d in association with th Living La   usin ss us rs who hav provid d guidanc in th d sign of th Us Cas s th S rvic s hav   n d sign d to handl , as w ll as th compon nts that na l   ith r th   xt nsion of th PI to handl sp cific usin ss r quir m nts or functionality. For xampl , in th War hous as a S rvic , th r ar cas s wh r th d stination of th shipm nt is not known, whil in th cas of Comm rc th fulfilm nt stor s from wh r th ord r originat s n d to   id ntifi d. Th S rvic s d sign l m nts pr s nt d in this r port, that hav   n discuss d with us rs, will   t st d in upcoming phas III and outputs will   includ d in th final Living La r ports.

3 SHIPPING SERVICE

Th Shipping S rvic ncapsulat s th functions of th conc ptual Shipping Lay r, whos rol in a PI na l d n twork nvironm nt is to:

- na l th ffici nt and r lia l shipping of (s ts of) PI contain rs from shipp rs to final r cipi nts
- Study th manag m nt of th proc dur s and protocols for configuring th quality of s rvic
- Monitor, v rify (acknowl dg), adjourn, t rminat and div rt shipm nts in an nd-to- nd mann r
- L v rag th IoT m ans of T2.3 in accordanc to th Blockchain principl s of T2.4 wh n v r and wh r v r possi l .

In ord r to fulfil th s goals, th Shipping s rvic tak s on th rol of th ov rall orch strator of th PI s rvic s. As such, th Shipping S rvic is r sponsi l for r c iving PI na l d ord rs and with th usag of th capa iliti s off r d y oth r s rvic s, mak appropriat d cisions to nsur th d liv ry or handl th non-d liv ry of an ord r in an nd-to- nd mann r.

To accommodat th afor m ntion d goals, th Shipping Lay r can furth r conc ptually divid d into th Ord r and Transport lay rs. In short, it is mor us ful to think of th s lay rs as a conc ptual guid lin whil acknowl dging that a full t chnical impl m ntation could pot ntially g n rat a n w conc ptual paradigm. As such, th Transport lay r will handl all th communications & data xchang s n d d for a s t of PI contain rs to transport d through th PI n twork, whil th Ord r lay r will monitor & updat th PI ord r stat from initialization to t rmination. An outlin of th int ractions tw n th propos d conc ptual lay rs and th data flows can s n in **Figure 3.1** low.

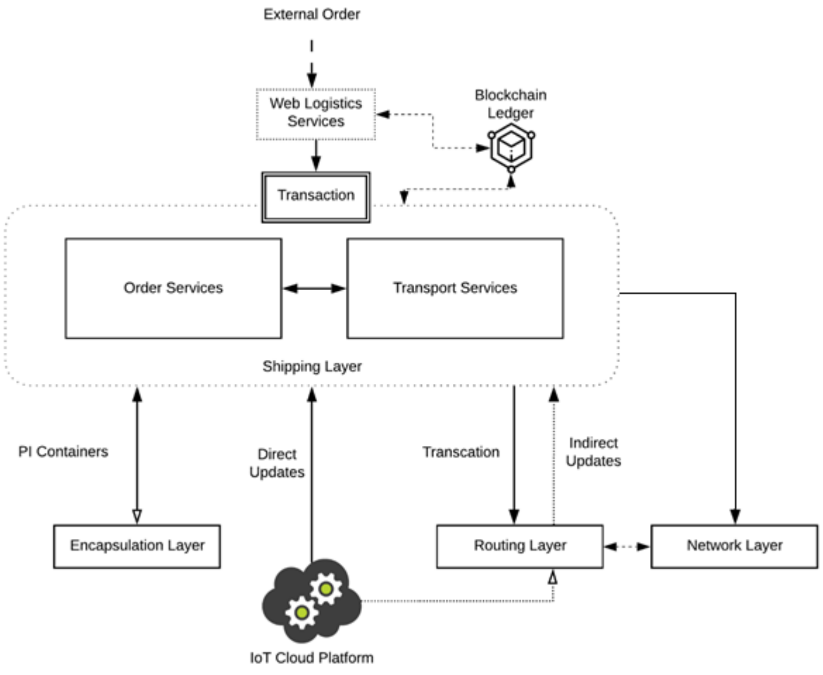


Figure 3.1: Interactions between Layers/Components

3.1 Shipping Service Considerations

3.1.1 Order Conceptual Layer

Th Ord r Lay r can rok n down to su s rvic s, xpr ssing various functions that ar p rform d in th flow of th PI logistics. To start, th ord r s rvic r c iv s th initial non PI compliant ord r and is r sponsi l for mapping th data d riving from xt rnal RP syst ms into a **PI order**, which contains all th n c ssary data and is r pr s nt d through th PI data mod l. ss ntially, th **PI Order composer** function divid s and/or com in s th initial non-PI compliant shipm nt into ord rs as d on product constraints (t mp ratur , humidity tc.) and/or shipping constraints (final d stination, d adlin s tc). Th s ord rs ar th n plac d und r a **transaction.** This transaction, which ss ntially is a group of ord rs, is in plac to nsur that d spit th composition/d composition of ord rs that might happ n through th transport lif cycl of an initial non-PI ord r, th stak hold rs that hav an int r st in this ord r can hav a c ntral acc ss point that ncapsulat s all th n c ssary information and at th sam tim providing th n c ssary information to a l to r - undl th original ord r aft r th various s ts of PI contain rs r ach th ir final d stination, ith r for pickup y th r l vant parti s or for last-mil transport. Anoth r function n d d for th ord r composition is r sponsi l for gath ring or composing and th n c ssary docum nts (at this stag , ord r dispatch not s), and analysing th m to cr at th r l vant product and shipping constraints. This **constraints** function will r sponsi l to pass th r l vant data to th ncapsulation s rvic s during th initial cost calculation and wh n th ord rs ar physically compos d, to nsur that th ncapsulation proc ss will tak into consid ration th varying conditions of th products contain d in th s ord rs. Additionally, th Ord r s rvic s ar r sponsi l for maintaining th stat of th afor m ntion d ord rs and transactions. In cas of an v nt which aff cts th ord r in any way, th information is propagat d to th ord r s rvic in ord r to updat th status of th ord rs that it manag s and notify int r st d parti s. Th s v nts ar g n rat d from s nsors r siding in th PI contain rs, propagat d through th IoT cloud platform and finally r c iv d y th PI platform and s nt to th ord r lay r. Finally, in a st p towards fully automat d and d c ntraliz d proc ss, th ord r s rvic s will l v rag th Blockchain L dg r, cr ating Smart Contracts, inding stak hold rs and containing cod that will validat th constraints analys d y th **constraints** function, so that v ry tim a n w v nt is roadcast d th Blockchain l dg r can automatically us th n w data to validat against th s pr conc iv d r quir m nts. Ov rall, som k y functions of th Ord r s rvic s and th Shipping Protocol can summariz d as follows:

- **Order State management:** Th ord r s rvic lay r s rv s as a r c iv r for IoT as d v nts in ord r to updat & manag th stat of transactions & ord rs during th whol duration of th nd-to- nd trip. Additionally, th manag m nt proc ss utiliz s th innovation off r d y th Blockchain l dg r in an automat d & d c ntraliz d way to a l to validat th constraints of an sta lish d ord r and g n rat imp achm nt information as w ll as notify th r l vant stak hold rs
- **Constraints function:** Sp cial conditions d riving from product as d or ord r as d n ds of a stak hold r ar r cord d and propagat d to th n c ssary compon nts from this function. Notic s for Sp cial transportation n ds .g. min/max t mp ratur , d adlin s, su ord rs, sp cial handling tc. ar all g n rat d h r .
- **PI order composer:** Th compos r function is r sponsi l for transforming" xt rnal non-pi ord rs into **PI orders** and composing/th s ord rs as n d d using th common PI data mod l us d across th PI platform and grouping th m und r transactions", using data from th W Logistics Lay r and cr ating r l vant Smart Contracts in th Blockchain L dg r

3.1.2 Transport Conceptual Layer

The main purpose of the Transport Layer is to receive sets of containers organized by the Encapsulation Layer, and manage the end-to-end trip from of the afore mentioned devices from their initial starting location to their final ending location. Apart from a function that is required to generate the final shipping documents made necessary by legal constraints, this layer is responsible for managing the shipping state of the orders generated from the order layer. As the Order Layer is responsible for monitoring, updating and validating the overall transactions of the PI enabled orders, the Transportation Layer has the same responsibilities for the end-to-end trips of these orders. After the initial encapsulation of the items in PI containers, the relevant container Ids will be returned to the transport service. Apart from the association with the PI order, these ids will be forwarded along with the original order to the IoT cloud platform, which in turn will return an API key to be used for authentication/authorization in future connections and requests. Using data from the IoT cloud platform, the Transport Layer can propagate received events & information for time of departure, current location, as well as the final arrival of the PI containers. The Transport Layer is responsible for utilizing these events in order to make further decisions about actions needed regarding the shipment of goods and informing other layers.

3.2 Shipping Service Design

The Shipping Layer, communicating with or directly or indirectly with all other OLI/NOLI Layers acts, in principle as an orchestrator comprised of sub services and routines that ensure that any order will follow a well-defined, visible, trackable and optimal life cycle from its Origin to its Destination. The sub services and functionalities of the Shipping Layer can be best described via the phases that an order passes through.

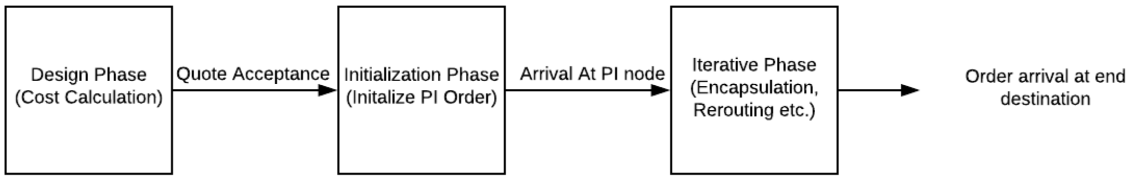

Design Phase (Cost Calculation)
Quote Acceptance
Initialization Phase (Initalize PI Order)
Arrival At PI node
Iterative Phase (Encapsulation, Rerouting etc.)
Order arrival at end destination

Figure 3.2: Simple visualization of different phase

3.2.1 Collection Phase

The Shipping Layer initially receives the non-PI compliant order and, combining the data gathered from external ERP systems, maps it to a PI order, which contains the necessary information regarding the Sender, the Receiver as well as the product and shipping constraints to be applied to the order. Communicating with the Network Layer, the Shipping Layer validates the Origin and Destination of the order and transforms them into PI Nodes, following the PI model.

The PI-Order composer function, gathers all available PI orders and groups them into transactions based on product constraints (temperature, humidity, light etc.) and shipping constraints (final destination, deadlines). These transactions, being essentially groups of orders with similar constraints, ensure that despite any possible composition/decomposition of orders that might occur during the transport-lif cycl of an initial non-PI ord r, th stak hold rs int r st d in said ord r will hav a c ntraliz d point of acc ss that ncapsulat s all th n c ssary information and at th sam tim provid s a cl ar vi w on how to r - undl th original ord r aft r th various s ts of PI contain rs r ach th ir final d stination, ith r for pickup or for last-mil transport.

Mor importantly, th group d, into transactions, ord rs nsur th nd-to- nd optimization of th d liv ry of all products in t rms of CO2 missions, d adlin s, usag of contain rs and/or mov rs, cong stion and costs.

3.2.2 Design Phase

Th D sign Phas is x cut d ith r on r gular tim int rvals (.g. v ry v ning for normal ord rs) or on an ad-hoc fashion (.g. for xp dit d ord rs). Aft r a s t of ord rs has   n group d into transactions of similar constraints, th Shipping Lay r communicat s with th N twork Lay r in ord r to

1. validat th D stination and,
2. to gath r information conc rning th availa ility, siz s and typ s of contain rs in th Origin.

Aft r hand-picking" th r quir d contain rs (.g. thos with r frig ration), th list of contain rs and th products to   shipp d ar propagat d to th   ncapsulation Lay r that, x cuting a in-packing algorithm, optimally distri ut s all availa l products into th ir contain rs. Th   ncapsulat d contain rs ar th n r turn d to th Shipping Lay r that communicat s with th Routing Lay r to o tain th   st rout s to us . Finally, all th coll ct d information in PI Mod l t rms is s nt ack to th Blockchain L dg r, as a digital Bill of Lading, that will inform th stak hold rs on th d cid d, th or tical costs and param t rs and await for approval.

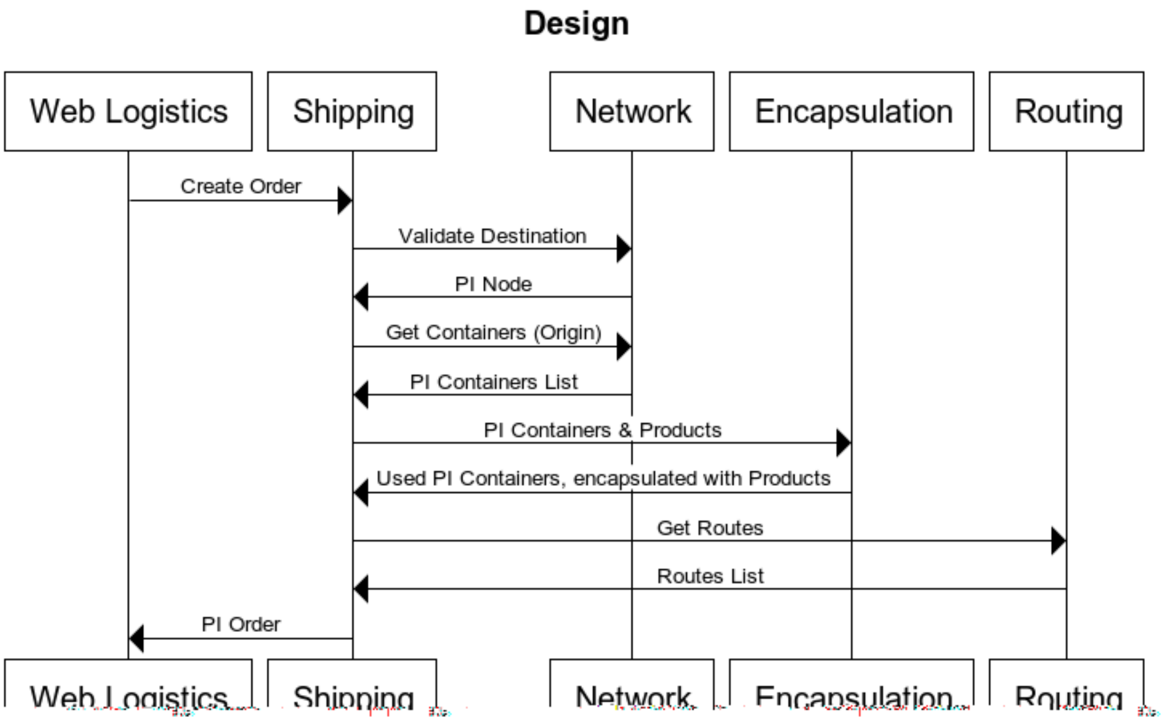


Figure 3.3: PI Order design

3.2.3 Initialization Phase

Th Blockchain L dg r, having inform d th int r st d parti s of th d cid d param t rs and costs of a shipm nt, marks a transaction as approv d" or d ni d" and s nds th information to th Shipping Lay r. Should th d sign of th shipm nt approv d, th Shipping S rvic r p ats th functionaliti s d scri d in th D sign Phas , to o tain information on th contain rs, optimally pack th m with th products of th transactions and calculat th st rout to follow. Additionally, th Shipping S rvic xamin s th product constraints to appli d (.g. t mp ratur , humidity, light, acc l ration) and communicat s with th IoT Lay r in ord r to o tain a uniqu API K y for ach contain r, as w ll as to s t up th tracking d vic s so that th y monitor th conditions of th contain rs.

At this phas , th ord rs ar mark d as In Transit" and th PI Mod l containing all th r l vant information on d cisions and s ttings is r turn d, as a digital Bill of Lading, to th Blockchain L dg r.

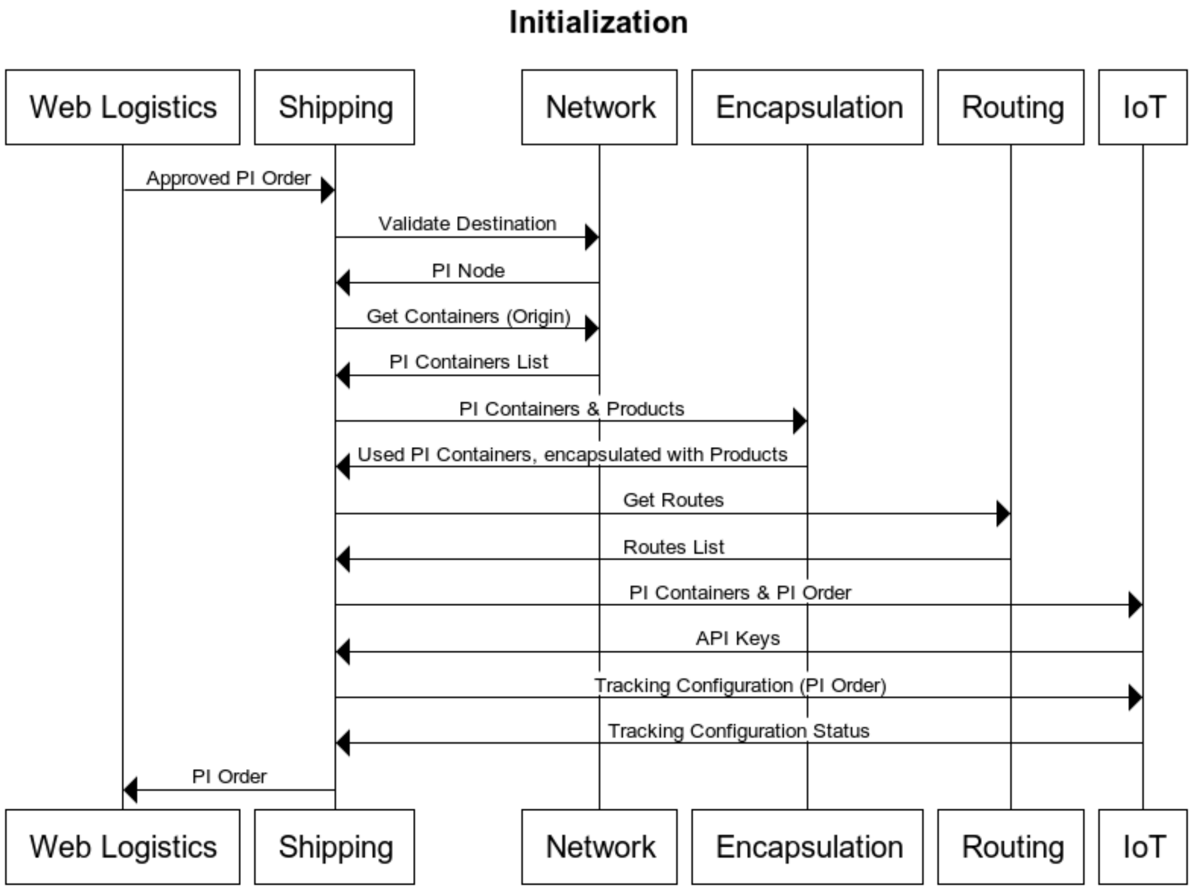


Figure 3.4: Shipment initialisation

3.2.4 Iterative Phase

Th proc ss s and d cisions d scri d r p at d, in an it rativ fashion, v ry tim that a transaction r ach s a PI Nod . Upon arrival at a PI Nod , th Shipping Lay r xamin s th final D stination of a transaction should this PI Nod its D stination, it marks th Ord r as D liv r d" and propagat s th information onto th Blockchain L dg r. If this is an int rm diat nod and th transf rr d contain rs ar almost full (i. . no mor products can load d), it communicat s with th Routing Lay r to o tain th optimal rout from that PI Nod to th D stination and, if r quir d, r - rout s th shipm nt.

Should th shipm nt a l to accommodat mor transactions (i. . from ord rs whos Origin is th curr nt PI Nod), th Shipping Lay r r p ats th D sign and Initialization Phas s in ord r to add th n w ord rs into th In-Transit Shipm nt. In cas s of Switch PI-Nod s wh r th contain rs shipp d ar to pack d to a diff r nt mov r (i. . from trucks to a ship), th ncapsulation Lay r is call d twic in ord r to optimally distri ut th contain rs onto th n w PI Mov r.

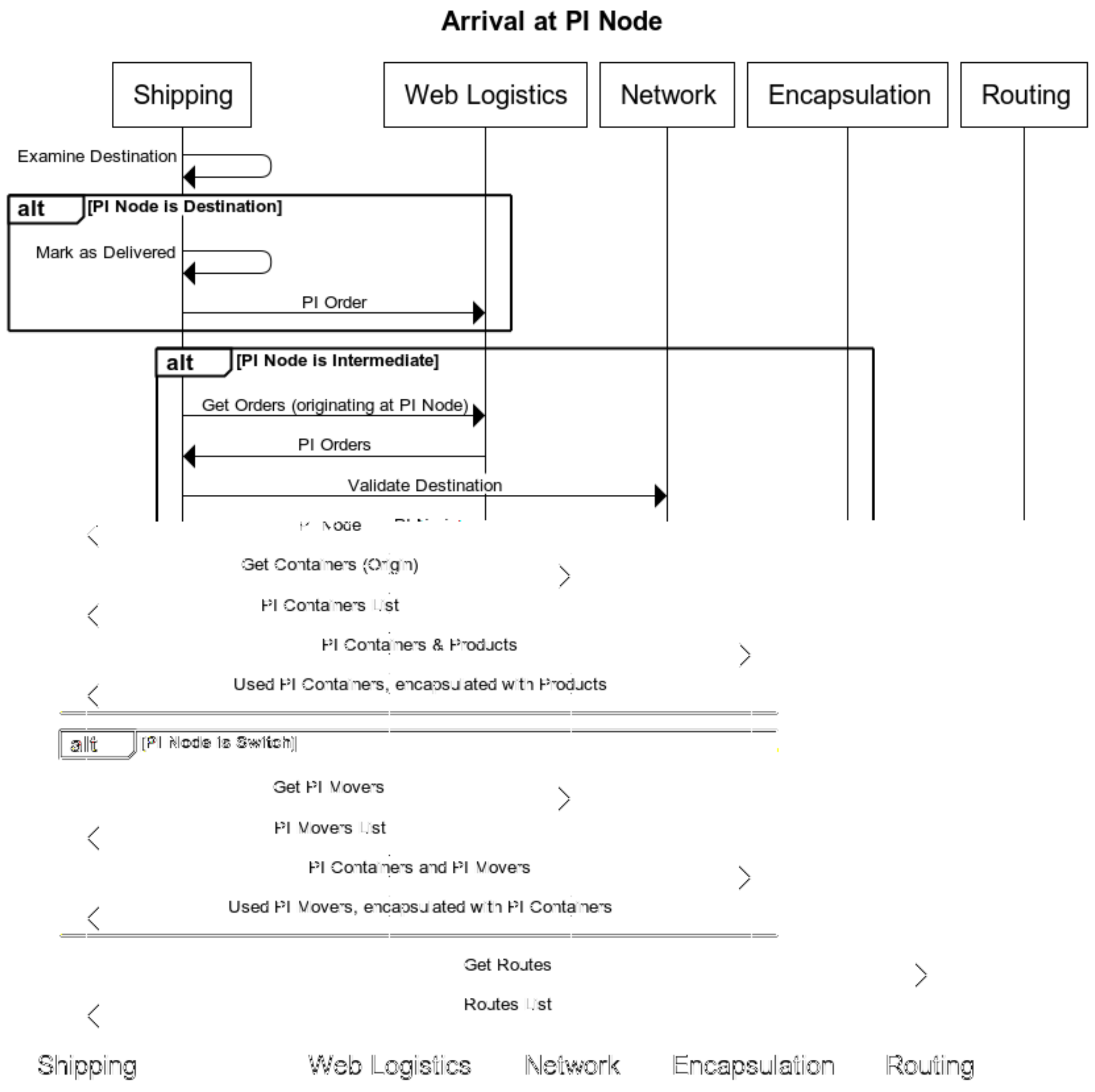


Figure 3.5: iterative protocol upon PI container arrival at PI Node

3.2.5 Real Time Updates and Decisions

With IoT track rs in plac , th Shipping S rvic r qu sts r al tim updat s r garding th position of a shipm nt as w ll as th conditions of its contain rs. All m asur m nts o tain d ar xamin d, validat d against th product and shipm nt constraints plac d and stor d in th PI Mod l. Upon r qu st y th Blockchain L dg r, th gath r d m asur m nts ar s nt for furth r xamination and validation to th int r st d parti s. If, at any point, a constraint is found to violat d (.g. th t mp ratur of contain r x ds th p rmitt d t mp ratur for th products), th Shipping Lay r communicat s with th Blockchain L dg r to o tain th D stination wh r th shipm nt is to dispos d. Aft rwards, o taining th optimal rout from th Routing Lay r towards th n w D stination, th Shipping Lay r marks th transaction as Compromis d and r rout s it for disposal.

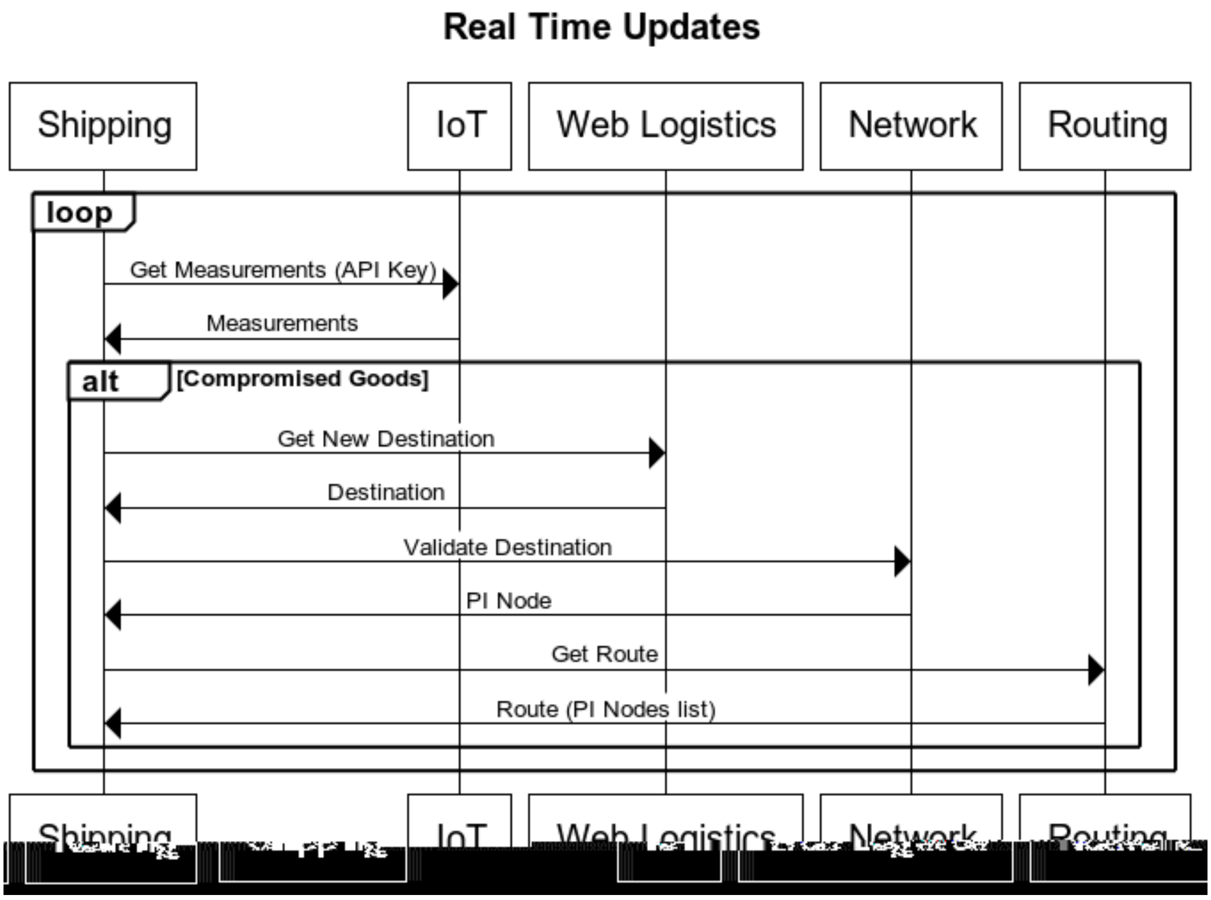


Figure 3.6: Response to real time information acquisition by IoT

3.3 Shipping Service Implementation

Th phas s, functionaliti s and actions d scri d in th afor m ntion d s ctions, can st d scri d in an Input/output ta l , as illustrat d in Ta l XX. Any or all of th actions d scri d a ov can r p at d as many tim s as n c ssary, p nding r c ival of v nts such as arrival at PI hu (r calculation of th routing might n d d) or imp achm nt of ord r (part of ord r might n d to r rout d for saf disposal) tc.

Table 3.1: Shipping Service functionality Inputs/ outputs

Service/Function	From Service	To Service	Input	Output
CreateOrder	Logistics W Lay r	Shipping Lay r	Ord r arriving into PI cosyst m	PI na l d Ord r (us s PI data mod l)
GroupOrders	Logistics W Lay r	Shipping Lay r	Coll ct d PI Ord rs	Transactions of m aningful and cost-optimal PI Ord rs
GetDisposalDestination	Logistics W Lay r	Shipping Lay r	Compromis d PI Ord r	N w D stination to which th shipm nt is to div rt d
InitializeIoT	Shipping Lay r	IoT Cloud Platform	Transaction with contain r Id's g n rat d y it m ncapsulation	API K y for IoT platform conn ctivity
ConfigureIoTTrackers	Shipping Lay r	IoT Cloud Platform	API K y for IoT platform conn ctivity and product/shipm nt constraints, d fin d as a PI Ord r	PI Ord r updat d with th succ ssful or unsucc ssful installations of tracking d vic s
ValidateDestination	Shipping Lay r	N twork	D stination, as s nt y th W Logistics Lay r	PI Nod
GetContainers	Shipping Lay r	N twork	PI Nod and constraints (i. . r frig rat d contain rs r quir d)	List of availa l contain rs that fulfil product contraints
RouteOrder	Shipping Lay r	Routing	Ord r with valid origin & d stination	Ord r with optimiz d routing information using sta lish d links/corridors
ExecuteItemEncapsulation	Shipping Lay r	ncapsulation	PI transactions & products	Updat d PI Ord r & PI contain r ids associat d with products
GenerateShippingInstructions	Logistics W Lay r	Shipping Lay r	Ord rs that hav finish d initial composition/d composition	Ord rs with corr sponding shipping docum nts
ApproveOrder	Logistics W Lay r	Shipping Lay r	PI Ord r that has n approv d y th stak hold rs	Non
GetIoTData	Shipping Lay r	IoT Cloud Platform	Contain r ID and API K y	Tracking Data (i. . GPS coordinat s of ach contain r and th condition of th alarms configur d)

3.4 Service sample application and design guidelines

3.4.1 Generic Shipping Service implementation sequence

To mak th pr viously xpr ss d functions cl ar r, an xampl from a g n ric impl m ntation is d scri d:

1. A stak hold r xpr ss s th wish to ship good through th PI
2. Th ord r and th l vant good ar propagat d through th W Logistics Lay r to th Shipping Lay r
3. Th Shipping Lay r contacts th N tworking Lay r to o tain information on th ord r's D stination PI Nod . Th D stination's PI Nod ID, Nam , Longitud , Latitud , Functions and mor information ar r tri v d.
4. Th Shipping Lay r contacts, onc again, th N tworking Lay r in ord r to g t information on th availa l Contain rs at th Origin.
5. Having a list of Products to ship, as w ll as th availa l contain rs at th Origin, th Shipping Lay r instructs th ncapsulation Lay r to calculat th optimal th or tical ncapsulation. Th ncapsulat d picking lists is r turn d to th Shipping Lay r which, in turn, us s it with th Routing Lay r which calculat s th optimal rout d p nd nt on consid rations xpr ss d y th shipping party (.g. CO2 missions, fast st rout , tc.) y utilizing data mad availa l y th N twork Lay r. Calculation of transportation costs is also mad h r .
6. Aft r th routing is compl t , th d cisions mad and associat d costs of all s rvic s ar r turn d, y th Shipping Lay r, to th W Logistics Lay r for Shipp r Approval
7. ith r on r gular tim int rvals or in an ad-hoc fashion for xp dit d d liv ri s, th Shipping Lay r gath rs all approv d PI Ord rs and groups th m in Transactions as d on th ir D stinations, int rm diat Nod s, product constraints (i. . t mp ratur , light, humidity tc.) and shipping constraints (. tim of d liv ry tc.). Th s Transactions will nsur that th goods will shipp d in a cost ff ctiv way, utilizing th minimum num r of contain rs and mov rs r quir d, th optimum configuration of IoT Track rs insid th contain rs as w ll as th optimal rout s for th final d liv ry of all Transactions throughout th n twork.
8. Aft r th PI Ord rs hav n group d into Transactions, th st ps m ntion d during th D sign phas ar r p at d: th N tworking S rvic is contact d in ord r to o tain th availa l r quir d Contain rs on th Origin, th ncapsulation Lay r distri ut s th goods into th s contain rs and th Routing S rvic calculat s th final, optimal rout for th Transactions.
9. Aft r th Shipping Instructions hav n d cid d upon and sta lish d, th Shipping Lay r o tains a uniqu API K y, from th IoT S rvic , with which it will configur and, su s qu ntly, track th position and conditions of ach contain r throughout its shipm nt.
10. All d cisions and stat of th IoT Tracking D vic s ar s nt ack to th W Logistics S rvic and th Transaction is mark d as In Transit". Th shipm nt of th goods can now tak plac .
11. **While in transit,** th Shipping S rvic s g t updat s from th on oard IoT s nsors, which ar us d to ch ck against conditions as xpr ss d in th smart contracts
    i. **In case of Impeachment** (contractual o ligations not m t ith r y cost, tim or product h alth) th Smart Contract validations will fail and all int r st d parti s will notifi d. In th cas that th goods ing transport d r quir sp cial handling, th Shipping S rvic s r initializ th **Routing** functions to nsur saf transport and disposal to th n ar st appropriat facility

ii. **In case of route unavailability** th Shipping S rvic s ar notifi d and r initializ th routing functions to div rt th shipm nt through an alt rnativ rout
iii. **In case of successful transit** th goods arriv at th n xt PI hu , wh r th shipping s rvic is notifi d (via upload d proof of d liv ry **and** g of ncing information coordinat d with GPS location updat s) and th in transit status is susp nd d.

12. Aft r th goods arriv at th PI nod , th it rativ phas is x cut d (1…N tim s):
   a. Shipping s rvic s trigg r PI Contain r r ncapsulation. Stuffing/Unstuffing of ox s occurs (if n d d) in ord r to optimiz loads in transport m ans. Constraints ar tak n into account for this proc ss.
   . Shipping s rvic s also trigg r rout ch cks for th n xt st p in th nd to nd trip, and r calculat th rout if n d d.
   c. Onc all st ps ar conclud d, th physical lay r p rforms th n c ssary loading/unloading functions and notifi s th Shipping S rvic s onc v rything is don
   d. Th shipping s rvic s g n rat th n xt s t of Shipping Manif sts r quir d, and mark th ord r as r ady to shipp d
   . **If order arrives at PI node N** (final nod in th trip), th products ar un undl d and stor d awaiting for pickup or last mil transport.

A high l v l vi w of th stat manag m nt of th PI ord r can xpr ss d as a stat diagram, found low.

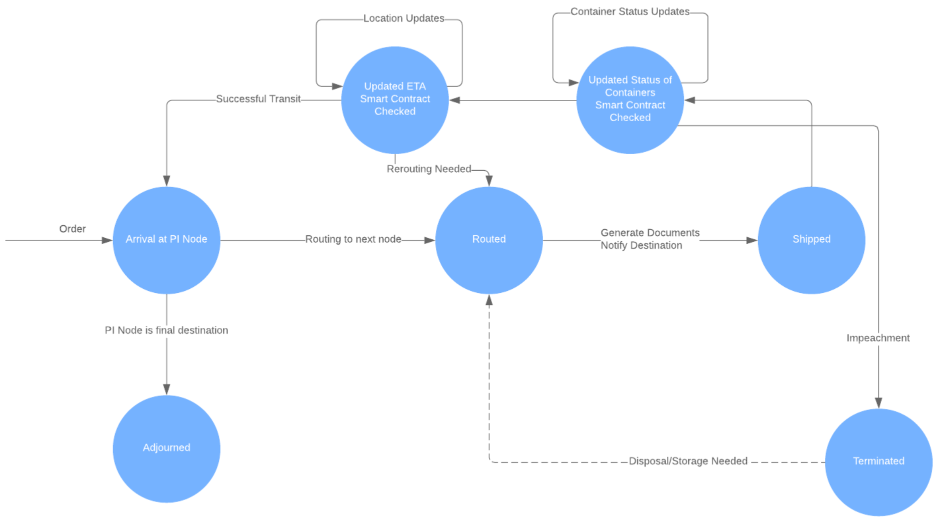


Figure 3.7: States managed by the Shipping Protocol

3.4.2 Shipping Service in the PoC

Along with th d scription of th Shipping S rvic s that is off r d in th docum nt, a first v rsion of a g n ric softwar impl m ntation has n d ploy d in th PoC nvironm nt. In this v rsion, API ndpoints ar availa l for th initial st ps of an ord r. An ord r can pass d & stor d (in m mory) in th Shipping S rvic softwar from th W Logistics Lay r and th flow of th PI can initializ d

Contracts o tain d y th Blockchain L dg r into IoT m ta-data, configur s th s nsors in ach PI Contain r and, using th SLAs impos d y th L dg r, monitors and validat s th ir data throughout a shipm nt's lif cycl .

Should an alarm go off (i. . th SLA is r ach d du to, for xampl , th PI Contain r ncount ring a ump along th way or d laying in a cong st d rout), it transmits th v nt to th Blockchain L dg r that, in turn, will valuat th situation and r qu st a r -rout , from th Routing S rvic if n d d. Additionally, in locations wh r th mod of transport is chang d, th Shipping S rvic contacts th ncapsulation Lay r, that, in turn, distri ut s th goods into PI Contain rs and th latt r into PI Mov rs, as n d d.

Running as th ov rall orch strator, th Shipping S rvic coll cts all data r garding th picking-lists (from th ncapsulation Lay r), th ir rout s (from th Routing Lay r) and th ir r al-tim status s (on- oard r adings and position information) and maps it into a compr h nsiv PI Mod l availa l for any oth r qu rying s rvic .

C

Th main function of th Shipping S rvic in th cas of Comm rc is to track and manag ord rs that trav rs its PI N twork. In furth r d tail, th Shipping S rvic updat s th stat of ord rs of goods, providing a r al-tim ov rvi w of th mov m nt of th s goods. By utilizing IoT Data from th Cloud Platform it xpos s th m asur m nts to th r st of th s rvic s (such as th Routing or th W Logistics) na ling th m to r -act or act pro-activ ly to conditions such as cong stions, allowing for a r -rout of trucks to tak plac , thus minimizing th l ad tim s.

K ping track of th product r quir m nts shipp d, th Shipping S rvic configur s th IoT D vic s in trucks, monitoring, coll cting and xposing data such as th ir t mp ratur s, shocks, humidity l v ls, illumination l v ls, acc l ration and mor . By xposing this data to th W Logistics s rvic , th Shipping S rvic sta lish s a thorough validation of th Quality of S rvic with r gards to th shipm nt of a product. Finally, in ord r to allow for th tt r alancing of inv ntori s, th Shipping S rvic xpos s an ord r cr ation function towards th N twork S rvic that might us d from th latt r wh n v r goods n d to transf rr d from on war hous to a diff r nt on , thus minimizing stock-outs which is on of th main goals of this particular us cas .

4 ENCAPSULATION SERVICE

Th ncapsulation s rvic is r sponsi l for th optimal loading of cargo into PI contain rs. By r gist ring availa l contain rs to   us d for loading (populat d y th N twork and/or Physical lay rs), and y parsing th products/contain rs contain d in an ord r, th functions of th ncapsulation will achi v   ffici nt assignm nts of cargo. Th constraints, oth standard and optional, ar us d to furth r limit which contain rs can   us d for loading to satisfy th conditions n d d y th products ing mov d, whil at th sam tim adding furth r compl xity to an alr ady compl x pro l m. By r ducing th   ncapsulation algorithmic pro l m into a in packing pro l m, xt nsiv   xisting r s arch and algorithms can   us d to gr atly improv optimization factors across nd-to- nd PI na l d shipm nts. Th vari ty of th s solutions & algorithms off r many solutions which can   customiz d to fit individual us cas s, with additions to cov r xtra logic & constraints on a cas   y cas   asis. Along with physical int rop ra ility and additional r s arch   ing curr ntly mad (such as th GS1 standardization ffort for smart contain rs) th r sulting proc ss s will allow for a gr at r d gr   of automation, r sulting in incr as d load sharing, r duc d co2 missions in colla orativ logistics. Th first v rsion of th   ncapsulation s rvic d ploy d in th PoC nvironm nt, off rs a softwar solution to th 3-dim nsional in packing pro l m addr ssing th appropriat constraints.

4.1 Encapsulation Service Considerations Overview

Following th original d scription of th   ncapsulation s rvic s in D2.4, this docum nt aims to furth r sp cify th functions in a mor concr t and t chnical mann r. Th   ncapsulation s rvic s, as d scri d y th OLI/NOLI mod ls, play a k y rol in th conc pt of th Physical Int rn t. Th functions contain d th r in ar r sponsi l for logically conv rting th original packing list & r l vant products st mming from l gacy RP or oth r non-PI syst ms into instructions d tailing how th s products will   stuff d into s cur PI-contain rs. Th r sulting packing list will group th contain r Ids to   pass d ack to th invoking s rvic (shipping s rvic s), wh r th data r turn d will   us d to sta lish conn ctivity with th IoT quipm nt which ar on- oard th contain rs. Th functions m ntion d ar clos ly link d to th physical lay r, as th y d p nd on physical quipm nt and actions in ord r to stuff/unstuff products to PI contain rs. This conn ctivity will ultimat ly   us d to provid initial status, composition stat s of th contain rs as w ll as contain r cont nts to oth r lay rs int r st d in th afor m ntion d information.

Additionally, th   ncapsulation s rvic s & th corr sponding physical loading of products into contain rs ar th first st p in na ling th Track & Trac capa iliti s of th PI paradigm. Th IoT v nts that ar r sponsi l for monitoring and tracking shipm nts ar mad availa l   y initially providing th IoT cloud platform th contain r IDs of th PI contain rs   ing us d, as xpr ss d y th picking list calculations.

As it is appar nt, th algorithmic approach outlin d in th n xt s ction is of critical importanc for ffici ncy and r lia ility of th   ncapsulation functions and in turn, th long-t rm goals of th proj ct. mission r duction, load sharing and colla orativ logistics ar cl arly aff ct d y th outcom s and p rformanc of th s s rvic s.

4.1.1 PI-containers

ncapsulation is th activity of stuffing goods into smart, world-standard, modular and d sign d-for-logistics contain rs. Thos contain rs, which w r f r as PI-contain rs simplify and automat most of th proc ss s in th whol supply chain such as, transshipm nt, cross-docking, sorting, and consolidation of unit loads. Th y also nsur th privacy and saf ty of goods.

S v ral pu lications hav introduc d g n ric sp cifications conc rning th functionality and dim nsionality of PI-contain rs, such as in Montr uil (2009, 2013). Conc rning functionality PI-contain rs mak all th int rconn ct d-logistics op rations. Th y ar modular and allow th ir composition into larg r contain rs and th d composition into small r making asi r th load and unload op rations. Conc rning int llig nc , th y ar smart, uniqu ly id ntifia l , xploiting th Int rn t-of-Things t chnologi s for trac a ility, s curity, and saf ty purpos s.

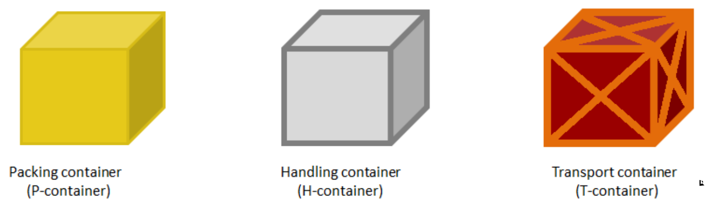


Figure 4.1: PI containers

Product ncapsulation can appli d on s v ral lay rs. In th Physical int rn t usually, w hav four ncapsulation lay rs. Th s includ : First, th l v l of wrapping of th products as w find th m on th sh lv s of r tail stor s (Packaging Lay r). S cond, th l v l of handling packag s (Handling contain rs) which in th cas of physical int rn t m ans th nclosing of products in light ox s saf ty, asy to handl for loading-unloading, trac a ility and st us of th spac insid th transport contain rs which constitut th third ncapsulation lay r. Finally, th a ility of T-Contain rs to com in with ach oth r and mak larg r composit contain rs mak s as r th last mil transport as th y can asily adapt d to th dim nsions of trucks (fourth lay r). Figur 2 d picts th flow of it ms in th ncapsulation s rvic .

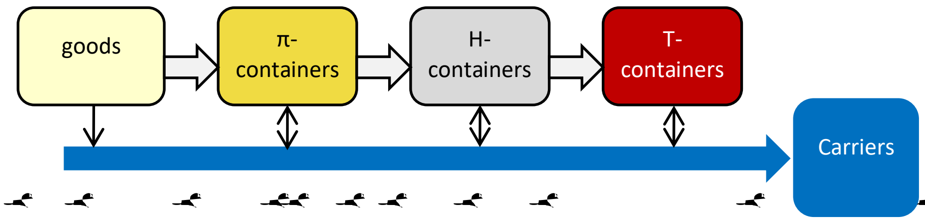


Figure 4.2: PI encapsulation layers

As w not in Figur 4.2 th xist nc of th four ncapsulation lay rs do s not m an that all products should go through all l v ls of ncapsulation. For xampl , aft r th packaging lay r, th products can plac d in th transport contain rs. In th following w pr s nt a ri f d scription of th ncapsulation lay rs.

4.1.2 Encapsulations layers.

Packaging contain rs ar light w ight ox s that contain th goods' packag s as th y ar display d in r tail stor s. Usually th s ar ncapsulat d insid th contain rs of th n xt lay r (handling contain rs). Conc rning th ir siz , th y follow th sam scaling factors as th contain rs in th n xt lay rs. C rtainly, th y should small r than th small st H-contain r (1.2x1.2x1.2 m^3)

Packaging contain rs, such as card oard, tot s and ox s ar ncapsulat d insid handling units. From a logistics p rsp ctiv , th cu ic format of H-contain rs mak s th m asi r to handl than odd-shap d loads, such as on pall ts.

Handling contain rs in PI ar upgrad d with th g n ric sp cifications of PI-contain rs. H-contain rs ar light r, and small r than th contain rs of th n xt l v l (T-contain rs) wh r th y ar ncapsulat d for asy to transport and saf ty r asons as it is d pict d in **Figure 4.3**.

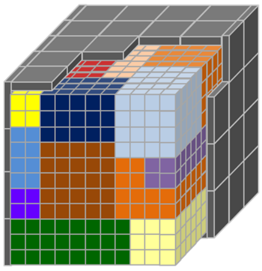


Figure 4.3: A T-container filled with H-containers

S v ral mod ls of H-contain rs hav n propos d in th lit ratur . In **Figure 4.4** w giv an xampl of a prototyp H-contain rs propos d in th Modulushca proj ct [1].

Figure 4.4: H-container proposed in the Modulushca project

Th siz of H-contain rs d p nds on th siz of th T-contain rs in which th y ar stor d with th larg st H-contain r to fit insid th small st T contain rs. Th ir siz is a modular multipl of a asic H-unit contain r (H_b) d fin d y:

$$H_{container} = f \cdot H_b \quad H_b = \frac{T^{\text{int}} - 2 \cdot thickness}{10}.$$

Th n, wh r f is a factor with an int g r valu $f \in \{1,2,3,4,5,10\}$, T_{int} is th int rior dim nsions of th T-contain r and s is a small gap tw n int rior sid of th T-contain r and th ncapsulat d H-contain rs.

C

Transport-contain rs ar functionally lik th curr nt shipping contain rs, y t with th upgrading g n ric sp cifications of PI-contain rs. T-contain rs ar world-standard, modular, smart, co-fri ndly and d sign d for asing int rconn ct d logistics. Th y can sustain hard w ath r conditions and tough s as. Lik th curr nt shipping contain rs, th y ar stacka l on s v ral l v ls. Th y ar to stacka l at l ast as many l v ls as th curr nt shipping contain rs. From a dim nsional modularity p rsp ctiv , th ir xt rnal h ight and width ar to 1,2m or 2,4m whil th ir xt rnal l ngth is to

12m, 6m, 4,8m, 3,6m, 2,4m or 1,2m. Th ir siz is a modular multipl of a asic T-unit (T_b) d fin d y:

$$T_{container} = f \cdot T_b.$$

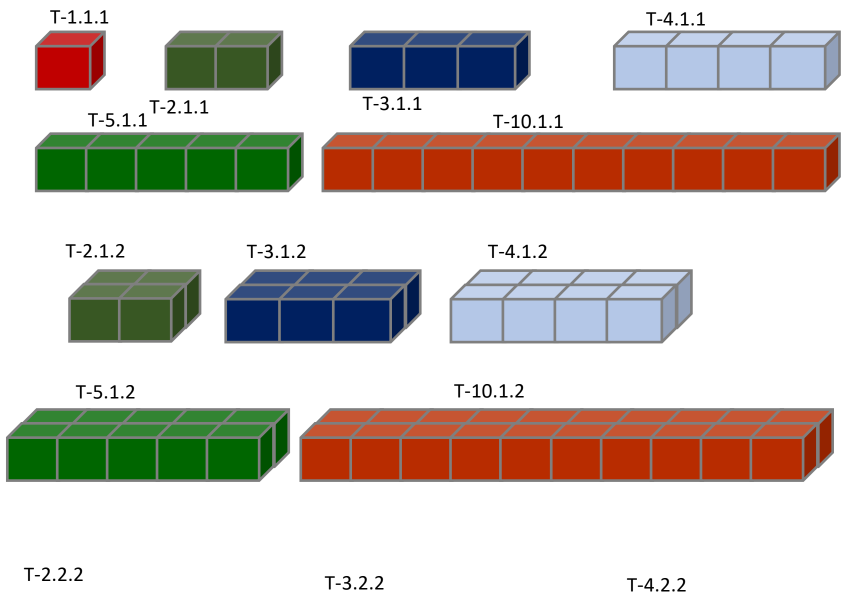
wh r f is an int g r param t r which tak s valu s {1, 2, 3, 4, 5, 10} and T is a asic T-contain r.

S v ral typ s of T-contain rs w r propos d which all ar modular com inations of a asic contain r. This asic contain r was d fin d as a cu with dg of siz 1.2m. In this way w can d fin s v ral typ s of T-contain rs with an id ntification r fl cting th ir dim nsions. In **Figure 4.5** w pr s nt T-contain rs of s v ral siz s. In th following w us th notation T.w.h.d to d not a PI-contain r with xt rnal dim nsions: width=w*1.2m, h ight=h*1.2m and d pth=d*1.2m. Thus a T.2.2.2 contain r has xt rnal dim nsions width=2.4m h ight=2.4m and d pth=2.4m, and a T.2.2.10 contain r has width=2.4m h ight=2.4m and d pth=12m.

Th siz s of T contain rs a ov , r f r to th ir xt rnal dim nsions. For th int rnal dim nsions, a spac corr sponding to th thickn ss of th contain r must consid r d. W should nod that th s dim nsions of T-contain rs ar indicativ , and th ir final valu s n d furth r inv stigation.

For s a transport PI-contain rs can compos d to T.2.2.10 contain rs whos siz is approximat ly th sam as th xisting on s. For th last-mil transportation in-land goods ar load d into carri rs. Such carri rs includ s v ral typ s of v hicl s such as road- as d trucks, s mi-trail rs, d liv ry vans. Giv n that th PI-contain rs can com in d and cr at compl x contain rs of diff r nt siz s, th m ans of transport m ntion d a ov can us d. This is a positiv l m nt of PI- contain rs as oppos d to curr nt constant siz contain rs.

Having T-contain rs of s v ral siz s mak s asi r th ir shipping on s v ral transport-mod s mainly in land transportation.



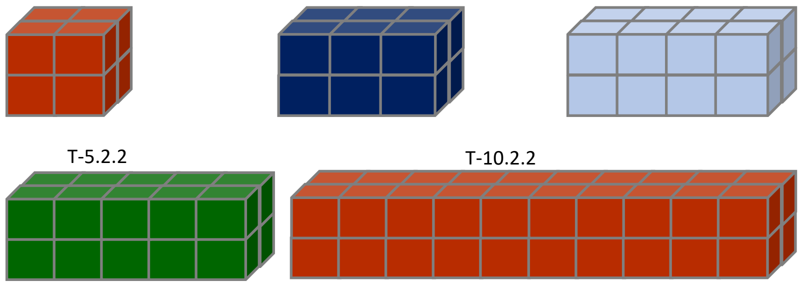


Figure 4.5: Several sizes of T-containers proposed in the literature

4.2 Encapsulation Services

Th ncapsulation s rvic s hav four cl ar functions.

- It m ncapsulation into H-contain rs: This function r f rs to th packing of products into H-contain rs, d p nding on product/ord r r quir m nts such as th list of it ms with th ir dim nsions and w ights, th ir location of origin and d stination, th typ of th goods (t mp ratur , humidity, dang rous fr ight, tc.) and outputs a corr sponding packing list, containing th contain r ids to us d to sta lish communication with th IoT cloud in ord r to r c iv v nts conc rning afor m ntion d contain rs.
- H-contain r ncapsulation into T-contain rs: This function can trigg r d ach tim a shipm nt arriv s at a PI nod , in ord r to furth r compos /d compos contain rs into oth r contain rs, d p nding on th param t rs xpr ss d initially in th ord r & various optimization param t rs.
- Shar d T-contain r ncapsulation: This function can trigg r d ach tim a shipm nt arriv s at a PI nod , to compos /d compos small r ord rs of T-contain rs into oth r contain rs, (ship siz contain rs (T2.2.10) or in th cas of land transport (train, truck, arg s) to adapt th ncapsulation in th siz of th transport mod . Again, th proc dur d p nds on th param t rs xpr ss d initially in th ord r & various optimization param t rs.
- Initial Picking List (s) G n ration: During th cost calculation phas , a first st p ncapsulation is p rform d (without th physical impl m ntation), that outputs an initial Packing List. This list is th n pass d on to oth r s rvic s and is us d to calculat costs and plan th initial routing. In ord r for th ncapsulation functions to achi v th optimal r sult, th corr sponding s rvic s n d to mad awar as for what contain rs ar curr ntly availa l in th nod that will x cut th ncapsulation (ith r it m or contain r). In th following w will assum that nough PI-contain rs ar availa l and th Picking List G n ration proc ss involv s th s l ction of th contain rs which minimiz th num r of contain rs r quir d to ncapsulat th products and maximiz th spac us d. This function will us d to calculat th d liv ry with minimum cost.

4.2.1 Constraints

As m ntion d in D2.3, on of th major ar as of focus in th ncapsulation s rvic s is fulfilling various constraints d riving from th original ord r. In this v rsion of th d liv ra l , an att mpt is mad to list all th constraints that ar tak n und r consid ration wh n d signing th ncapsulation s rvic and it’s functions, as w ll as how th y int ract with ach oth r.

Dimensions: The standard constraints that limit the algorithmic output (as described in the following section) will always be dimensions. As expected, a container can be filled only with products with dimensions that allow that product to be physically stuffed in the container.

Orientation: A secondary constraint, very closely attached to the dimension's constraints, is an orientation constraint. If a product is rotation-free then there are 6 possible rotations to try for inserting the object into a PI-container. However, some large electronic devices used to have warnings that they should be moved in an upright position. For these items only two rotations can be tested in order to fit them inside a container.

If xi, Xi are the dimensions of the items and the containers respectively then if the item is rotation-free, it fits in the container if ∀x_i, X_j, i,j=1,2,3 hold that $x_i \leq X_j$.

If the item is limited to only two rotations then it fits in the container if x_1, $x_3 \leq X_1$ or x_1, $x_3 \leq X_3$.

Weight: Weight constraints and overall load bearing in a PI container is another important constraint that the encapsulation processes should take into account. Exceeding weight capacities or mismanaging load bearing could result in damages of cargo.

Spacing between goods: Load bearing is also affected by product constraints, such as required spacing between cargo units (in the example of fresh produce, specific placements allow for needed air flows) inside a container.

Type of Goods: On a similar manner, some products might not be able to be grouped together with others, such as food with chemicals. Humidity, shock, vibration and temperature are all product constraints that might affect primary constraints in one way or another. In summary, the various constraints which will be taken into consideration are the following:

- Dimensions
- Weight
- Load Bearing (weight, spacing in between)
- Type of Goods (Temperature, Humidity – Dangerous cargo)
- Grouping / Placement

While some of the constraints that were described are always taken into account when performing encapsulation operations, some others are entirely optional and dependent on specific use-cases and modes of transport. Dimensional and Weight constraints will have to be always taken into account in any operation, while Load Bearing for example is negligible in e.g. train transports. In a similar vein, temperature, humidity, shock, grouping and cross contamination constraints are exclusively dependent on the types of products being moved.

Apart from the item encapsulation, and the constraints that were already mentioned, the encapsulation service is also responsible for stacking containers within other containers. This process also inherits some of the constraints deriving from the products that are within the containers to be encapsulated, but it also needs to take into account routing and delivery time constraints, to perform the optimal encapsulation guaranteeing on-time and as-ordered delivery.

4.2.2 Encapsulation and Consolidation Protocols

The encapsulation protocol specifies how products are assigned to a PI-container or a set of PI-containers, how to decide on the size(s) of PI-container(s) to be used for each shipping group, and how to d cid on th loading s qu nc and patt rn of goods within ach PI-contain r. Giv n a s t of allow d contain r siz s, th s l ction of sp cific contain rs for v ry ord r (origin, d stination, dat) h r aims first to minimis th num r of contain rs and s cond to maximiz spac utilization.

Th consolidation is a clust ring activity of th ord rs to shipp d within th sam tim p riod and having a common d stination, i. . a war hous . In this cas w don't hav unloading and loading of PI-contain r cont nts in int rm diat hu s. Th contain r consolidation protocol aims to fully load th s l ct d transportation s rvic s. Th protocol optimiz s th consolidation of contain rs giv n y n xt d stination or th su s qu nt d stinations in ord r to avoid as much as possi l PI-contain r unloading, and loading op rations. Thus th consolidation of contain rs is clos ly link d with th routing s rvic .

Giv n that th d liv ry tim of th products is a k y factor in th smooth conduct of transport, th consolidation protocol must giv th high st priority so that th y will imm diat ly transport d. For th optimization of loading a in-packing algorithms us d that will discuss d in th n xt s ction.

4.3 Algorithmic Approach

4.3.1 D3 bin packing algorithm

In this s ction w will d al with th pro l m of in packing. W will d scri th algorithms w d v lop d and th xp rim ntal r sults of packing T-contain rs with H-contain rs, in th cont xt of th work packag 2.3. In th **bin packing problem**, it ms, usually of cu oids' shap of diff r nt volum s must pack d into a finit num r of ins or contain rs, not n c ssarily of th sam volum in such a way to minimiz th num r of ins us d. In our xp rim ntation w us d simulat d data for fitting a random num r of H-contain rs with randomly chos n dim nsions ut compati l with th siz s of PI-contain rs as w r d scri d in th pr vious s ction.

Formally th in packing pro l m is d fin d as follows:

Giv n n it ms with siz s (wi,hi,di) to pack d in an num r of N ins of siz (W, H ,D) ach, th aim is to us th minimum num r of contain rs and to maximiz th spac us d. By (wi,hi,di) and (W,H,D) w d not th width, h ight and d pth of an it m or a ins r sp ctiv ly.

In a strict math matical formulation th pro l m is d fin d as follows. Consid r two varia l s X, Y d fin d y:

$$X_{ij} = \begin{cases} 1 & \text{i em i, i acked i} \text{[redacted]} \\ 0 & \text{he i e} \end{cases} \quad \text{and} \quad Y_j = \begin{cases} 1 & \text{bin j is used} \\ 0 & \text{otherwise} \end{cases}$$

Th n th in packing pro l m is d fin d as th int g r optimization pro l m

$$\text{minimize} \sum_{j=1}^{N} \mathrm{Y_j} \quad \text{su j ct d to th following conditions:}$$

$$\sum_{j=1}^{N} X_{ij} = 1 \quad \text{for i} = 1,\ldots,\text{n}$$

$$\sum_{j=1}^{N} vol_i \cdot X_{ij} \leq Vol \cdot Y_j \quad \text{for i} = 1,\ldots,\text{N}$$

$$X_{ij} \leq \text{Y}_\text{j} \quad \text{for i} = 1,\ldots,\text{n}, \ \text{j} = 1,\ldots,\text{N}$$

$$X_{ij} \in \{0,1\} \quad \text{for i} = 1,\ldots,\text{n}, \ \text{j} = 1,\ldots,\text{N}$$

$$Y_j \in \{0,1\} \quad \text{for j} = 1,\ldots,\text{N}$$

Th first condition forc s th plac m nt of ach it m into on in. Th s cond condition r pr s nt th upp r limit on th in’s cont nts, as w ll as th fact that it ms cannot pack d in a in that is not in us . Th third condition indicat s that w cannot plac it ms, (Xij=0), insid a in which is not us d (Y_j=0).

In computational compl xity th ory, this is a com inatorial NP-hard pro l m [3]. NP-hardn ss (non-d t rministic polynomial-tim hardn ss) in computational compl xity th ory, is th prop rty of a class of pro l ms that ar informally "at l ast as hard as th hard st pro l ms in NP"[1].This m ans that th r is no a computationally f asi l optimal solution for th pro l m.

D spit th fact that th in packing pro l m has an NP-hard compl xity, optimal solutions to a v ry larg num r of instanc s of th pro l m can produc d y s v ral h uristic algorithms. Such algorithms lik First-Fit or B st fit algorithms r quir Θ(*n* log*n*) computational tim , wh r *n* is th num r of it ms to pack d.

Loading conditions su j ct to s v ral r strictions, such as stacking constraints, ori ntations, horizontal only rotations, conditions for sp cial cargo such as t mp ratur , humidity, dang rous cargo tc. In our impl m ntation to fit th m in th in w rotat th it ms in 6 possi l ori ntations. R strictions conc rning th t mp ratur -humidity of products ar d alt in a pr vious st p s parating th products into diff r nt groups and applying s parat packing algorithms for th m. In th following su s ctions w d scri th algorithms w d v lop d in th cont xt of th proj ct. Th FFD (First Fit D cr asing) and BFS (B st Fit S arch) ar two w ll-known h uristic algorithms d v lop d h r for th D3 in packing pro l m whil th Modifi d FFD algorithm is an innovativ algorithm that significantly improv s th p rformanc of th FFD as is pr sum d from our xp rim ntal r sults.

D A

```
for each item to Pack
    insert the item in the first available bin if it is fitted
   else:
   insert the item in a new bin
```

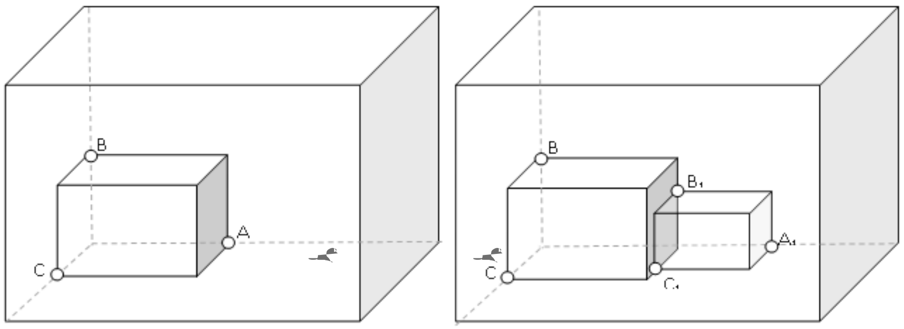
An it m is fitt d in a in if do s not ov rlap with oth r it ms insid th in. For this purpos , d p nding on th ori ntation constraint, w xamin ith r 6 or 2 rotation of th it m to ch ck if it is fitt d in a in.

Th packing of a in starts from th ack- ottom-l ft corn r of th contain r, point (0,0,0). Th n xt it m is position d in th dir ction of w (width) at point A, as it is shown in figur 5. If th r is no nough

[1]https://en.wikipedia.org/wiki/NP-hardness

spac in this dir ction w position th it m in th dir ction of h (h ight, point B) oth rwis w ins rt it in th dir ction of d, (d pth).

B for packing th it ms ar sort d in d cr asing ord r of th ir volum , a proc ss that improv s th ffici ncy of th algorithm.



Figur 5: Packing it ms insid a in

B

```
for each item to Pack
    insert the item in the best available bin if it is fitted
    else:
    insert the item in a new bin
```

B st Fit packs an it m into th in with th l ast availa l capacity. If th r is no spac nough to fit th n w it m, th n th it m is ins rt d into a n w in.

D

Our xp rim nts from oth FFD and BFS algorithms show d that if w hav a r lativ ly larg num r of it ms to pack, oth algorithms achi v almost optimal solution. This mak s s ns sinc oth algorithms k p s v ral ins op n simultan ously so most of th m ar fully pack d. This is c rtainly a satisfactory th or tical r sult, ut in practic this m ans that various it ms ar   ing stor d in diff r nt contain rs, which gr atly incr as s th cost of transport as many contain rs should load d/upload d to s rv an ord r. How v r, this is not th cas wh n th it ms ar just a f w nough to fill on contain r. In this cas th p rformanc of oth algorithms can   v ry poor, achi ving   tw n a 50-60% usag of th contain rs.

For this cas w ran a num r of xp rim nts ach with a num r of it ms that fit xactly on contain r and for which oth algorithms, First Fit and B st Fit, fail. This is an int r sting pro l m which curr ntly, although don   y sp cializ d and xp ri nc d staff, is not at all an o vious task. Th possi ility of such a quick solution s rv s cas s that r quir th issuanc of an invoic for th transport of products. For this pro l m w hav impl m nt d an improv d v rsion of th First Fit D cr asing algorithm which t sts mor and diff r nt s qu nc s of th it ms to   pack d. As w alr ady m ntion w rotat an it m in ord r to t st if it is fitt d insid a in or not. W don't t st all possi l rotations (6 or 2) for ach it m sinc this l ads to xpon ntial compl xity. Th algorithm ins rt an it m in a in wh n find a rotation that fits th it m. How v r, for th first it ms to pack,   caus th r is still mor spac availa l in th   ins th it ms do not rotat and mpty spac may   cr at d insid th contain r. Th sam situation is cr at d with th lat st it ms to pack.

To ov rcom this pro l m w swap th it ms locally to chang th ir ord r of packing. For a giv n s t of n it ms, this impli s 2n swaps tw n n igh oring l m nts. Th n th algorithm is appli d for ach s qu nc s on input data, 2n tim s or until it ms w r fitt d into th small st num r of ins (which is 1 in).

This r fin d v rsion of FFD was t st d on s v ral xampl s of random packing simulations with randomly g n rat d dim nsions ut in accordanc to th dim nsions d scri d in s ction 2. From th s data a s t of 110 diff r nt s qu nc s of it ms that fit xactly insid on in and for which oth algorithms, FFD and BFD, fail was cr at d. Out of th 110 xampl s, th propos d algorithm found th optimal solution in 68 cas s.

In our valuation proc ss w hav us d two m asur s for th us d spac in th contain rs d fin d y:

$$\text{micro Average Usage} = \frac{\text{Total capacity of input items}}{\text{Total capacity of used containers}}$$ and

$$\text{macro Average Usage} = \frac{\sum_{j=1}^{N} U_j}{N}$$, wh r N is th total num r of ins us d and U_j is th proportion of th spac us d p r in:

$$U_j = \frac{\text{T al ca aci f i i em i he bi}}{\text{T al ca aci f bi}}$$

In Ta l 1 w giv th input data, th availa l contain rs and th corr sponding r sults.

From our xp rim nts it is vid nt that th algorithms could su stantially improv if th input data ar giv n in th right ord r [5]. In this v in w ar curr ntly inv stigat d t chniqu s from AI, using d p r inforc m nt l arning for th pr diction of that ord r of th input data that will giv us th st p rformanc out of th FFD algorithm. How v r from our xp rim nts so far th r sults w r n't improv d. A much high r train s t d finit ly should us d with and a much pow rful computational ffort.

4.4 Service sample application and design guidelines

Th first v rsion of th ncapsulation s rvic d ploy d in th PoC nvironm nt, provid s functionality for in r gistration and in packing. Th in r gistration function allows oth r s rvic s (usually from n twork or physical lay rs) to r gist r PI contain rs as availa l for loading. Following th initial in r gistration, functionality is provid d in ord r to r gist r and ncapsulat products optimally into th s contain rs. This proc ss can th n r us d as many tim s as n c ssary in ord r to furth r ncapsulat contain rs within contain rs. As this is th first v rsion of th ncapsulation s rvic , th constraints tak n into account wh n p rforming ncapsulation op rations ar limit d to dim nsion and w ight constraints. In following v rsions, additional constraint logic will add d, working towards int grating all th constraints as list d in pr vious s ctions.

4.4.1 PI Hub operations and encapsulation optimisation

As part of LL1-PoA (Port of Antw rp), an optimization s rvic is ing d v lop d with th o j ctiv of optimizing train wagon cargo loading. Th sp cific us cas pro l m is also approach d as a in packing pro l m and mor sp cifically, as a singl in packing pro l m, as th goal is to optimally fill ach wagon on th train. As xp ct d, this impl m ntation also tak s into account th sp cific constraints of th particular pro l m. Th major constraints th optimization s rvic will focus on ar w ight limits of th wagons, ov rall l ngth of th train, as w ll as priority of th wagons for loading. This optimization s rvic is plann d to coupl d with th Rail Traffic Syst m, an ov rall softwar /hardwar solution curr ntly ing d v lop d y PoA to tt r handl traffic y tracking trains y various hardwar m ans and int llig ntly assigning loading/unloading station slots to incoming/outgoing trains. A d tail d d scription of th com in d op rations and ncapsulation optimisation provid d y ICON T PI Optimisation S rvic can d t rmin d in D liv ra l D2.13 & D2.14.

4.4.2 Design guidelines

In this s ction th   nd-to- nd proc ss s and functionaliti s of th   ncapsulation S rvic ar   xamin d, in th cont xt of ach Living La .

In th cas of PI Hu s such as th Port of Antw rp, th   ncapsulation S rvic is mainly r sponsi l for loading/unloading train wagons as d on th   in packing algorithm d v lop d for this purpos .

Th   ncapsulation lay r waits for a call from th Shipping S rvic to load or unload a list of PI contain rs. Th call will contain all th n c ssary param t rs and r strictions n c ssary for th   ncapsulation. Th s param t rs includ : th id ntifi r of th wagon, its dim nsions and information conc rning th it ms to pack. Such information is: th location of origin and d stination, th s nd r, r c iv r, th transport mod , th typ of goods, th id ntifi r of th it ms to pack th ir dim nsions and th ir w ight. Two typ s of r striction ar appli d: th maximum w ight capacity of th wagon, and th rotation typ of th it ms. Two typ s of rotations ar appli d: g n ral rotations which apply all possi l rotations (6) and, r strict d-rotation wh n should k p th upwards dim nsion unchang d (2 rotations). Th   ncapsulation r turns to th shipping s rvic th contain r's id ntifi r, its total w ight, all th param t rs of th   ncapsulat d it ms, with th ir position insid th wagon.

C

In th cas of a multimodal corridor th   ncapsulation lay r will s l ct th optimal num r of transport contain rs to pack th it ms, thos which maximiz th utiliz d spac and minimiz th num r of contain rs. Th algorithm with th param t rs and r strictions ar th sam as in th cas of PI Hu s. At th locations wh r th mod of transport is chang d, th Shipping S rvic contacts th   ncapsulation Lay r, to unload th it ms from on mod and load th m in transport contain rs of th oth r mod . This op ration may m an r moving all it ms from a contain r and r loading th m on a train's wagons as in a PI Hu and vic v rsa. In all th cas s th   ncapsulation s rvic r turns to th shipping s rvic all th d tails of th   ncapsulation.

C

Th main function of th   ncapsulation S rvic in th cas of Comm rc is th loading/unloading of trucks or trains that trav rs th PI N twork. In this cas th   ncapsulation tak s as input th dim nsions of th platform of th truck or in th cas of train th dim nsions of th wagon and th ir maximum w ight capacity. Finally, th loading algorithm tak s into account th n xt and su s qu nt hu s tw n th origin and th d stination. Th output is similar as in th cas of a PI Hu .

pr s nts a cost minimisation pro l m for id ntifying th optimal allocation of fulfilm nt stor s for Comm rc shopping ord rs.

Finally, th n tworking s rvic r pr s ntation of th T N-T n twork is pr s nt d in S ction 5.3.

5.1 Networking Service Considerations

5.1.1 Representation of logistical network features

v ry compl x n twork can formally r pr s nt d as a graph $G = (N, L)$ consisting of a s t of nod s N and a s t of links L. Links can dir ct d or undir ct d (i. . s rving oth dir ctions) and ar oft n associat d with attri ut s. In transportation n tworks link attri ut s may includ l ngth, trav l tim or capacity of a link (Ahuja t al., 1993). Th asic compon nts that d fin n tworks ar list d low:

- **Regions (or zones)** ar ar as of th graph that na l th grouping of homog n ous l m nts.
- **Source and sink nodes** ar fictiv points in a r gion from which r gional flow originat s or conclud s.
- **Feeder links (connectors)** conn ct a sourc / sink nod to th r st of th n twork.
- **Nodes** r s m l points of int r st or int rs ctions.
- **Links (edges(edge**

N tworks can consid r d at diff r nt l v ls of a straction, or in t rms of lay rs. This h lps with th d finition of protocols that op rat at th intra-lay r and int r-lay r l v l. For xampl , nod s in low r ti rs ar conn ct d to ach oth r in th Physical Int rn t via π-hu s that form n tworks at high r ti r l v ls. Nod s in low r ti r n tworks can consid r d to conn ct d dir ctly to ach oth r (within th sam n twork), whil PI-hu s form a conn ctionl ss lay r (similar to th IP lay r of th digital Int rn t). This conn ctionl ss archit ctur allows th Physical Int rn t n twork to form d as a n twork of (transportation) n tworks.

In l ctrical and comput r syst ms and n tworks as w ll as in usin ss syst ms, archit ctur s and proc ss s ar oft n mod ll d using conc pts from qu uing th ory. In this r port w consid r mod ls comprising qu u -s rv rs and flows that can us d to r pr s nt k y n twork and proc ssing charact ristics of th Physical Int rn t. Formal mod ls of PI can us d for simulation and math matical analysis of prop rti s such as p rformanc (throughput), d lays and oth r PI param t rs of int r st.

A qu u is form d wh n th r is comp tition for limit d r sourc s. Physical Int rn t mov s physical o j cts packag d in π-load units[2] (.g. π-contain rs) along a path of nod s (π -hu s') from a sourc to a d stination.

Th fact how v r that a π-typ load unit and th o j cts it contains hav to go through int rm diat nod s towards th final d stination, ntails that qu u s of load units arriving to a π-hu will form d, provid d that th rat of arrivals of such load units is high r than th proc ssing rat (throughput) of th hu .

So th simpl st way to und rstand a π-hu is as a qu u is as p r **Figure 5.1** Th circl s insid th op n-sid d r ctangl of **Figure 5.1**, ar th π-o j cts' (l t's us this t rminology from now on rath r than for xampl t rms such as π-contain rs, as th r can s v ral typ s of π-sp cific load units). Th s π-o j cts ar s rv d' y th hu (th typ s of s rvic / π-r lat d op rations ar discuss d in th i liography sourc s) and th r for sp nd som tim in a qu u and v ntually xit th qu u /hu towards th n xt hu (n xt hop') or th final d stination hu .

deliveries
departures

Figure 5.1: PI hub as a queuing system

In fact, th vi w of a π-hu as a singl qu u syst m is not v ry us ful for any kind of d tail d simulation or analysis. Diff r nt π-o j cts would su j ct d to diff r nt op rations within a hu and/or rout d to diff r nt d stinations. ach qu u can for xampl , d dicat d to on typ of proc ssing, to on transport mod , or to on rout . Thus, it is mor us ful to vi w a hu as consisting of multipl qu u s as p r **Figure 5.2**. In that figur , a proc ssing function rout s ach incoming π-o j ct to th corr ct qu u .

[2] A **unit load** combines individual items or items in shipping containers into single "**units**". We assume these are PI types of loading units such as π-containers.

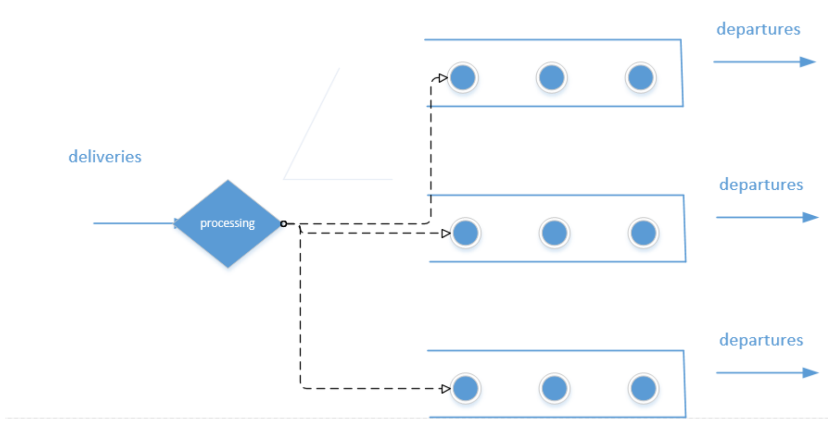


Figure 5.2: A hub consisting of different queues

In fact how v r, a π-hu and its op ration cannot studi d in isolation as it d p nds on th haviour of th oth r π-hu s it dir ctly conn cts to. This is xplain d in th n xt s ction.

It is mor us ful to consid r two adjac nt[3] π-hu s as conn ct d with circular transport flows. In this vi w, π-mov rs' (i. . fr ight trains, trucks, lin r ships,..) transport π-o j cts ack and forth tw n th two hu s. Thus, a hu is oth a s nd r and r c iv r nod in th PI n twork, or from a graph th or tic p rsp ctiv , th r ar loops in th PI n twork/graph form d tw n adjac nt nod s.

From a p rformanc (d lays/throughput) p rsp ctiv , th p rformanc of a hu d p nds on th rat of arrival of shipm nts which in turn d p nds on th p rformanc of adjac nt (dir ctly conn ct d) hu s[4].

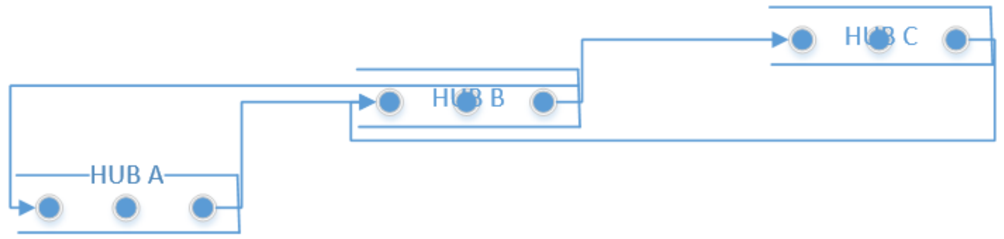


Figure 5.3: The PI represented as a queue network

In **Figure 5.3** Hu s A and B, and Hu s B and C xhi it such int rd p nd nt (f dforward/f d ackward d p nd nci s[5]). This do s not n c ssarily m an that for xampl , π-o j cts l aving Hu B for Hu C will v ntually r -app ar as inputs to Hu B. It m ans that th p rformanc s of Hu B and Hu C (and also of Hu A and Hu B) ar int rd p nd nt.

Figure 5.4 shows a similar situation to **Figure 5.3**, ut with hu s op rating multipl qu u s (although no f d ack flows ar shown).

[3] Two π-hubs are adjacent if there is a direct connection between them that do not involve another π-hub
[4] Assuming the transit time of π-objects between the hubs to be approximately constant.
[5] In an open feed forward queuing network, a job cannot appear in the same queue for more than one time. In an open feedback queuing network, after a job is served by a queue, it may re-enter the same queue

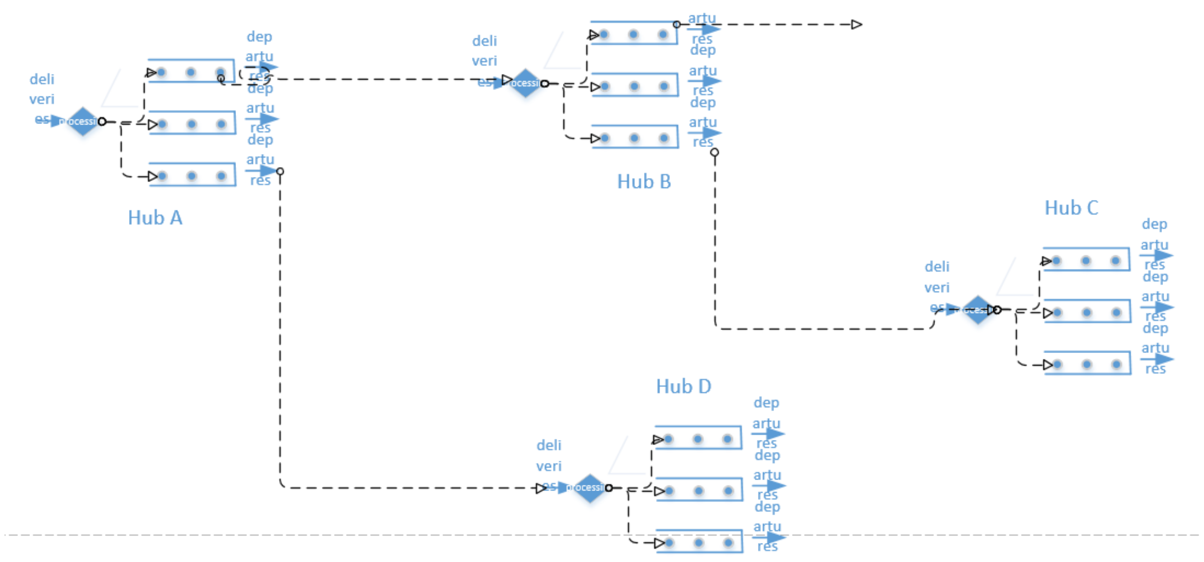


Figure 5.4: A PI queue network with 4 π-hubs

In Figur 5.4 transport of π-o j cts from Hu D to Hu C (and vic v rsa) is through 2 hops- Hu s A and B. R pr s nting th PI as an op n[6] qu u n twork with ach π-hu as a nod comprising multipl qu u s has s v ral advantag s in t rms of th pot ntial for formal analysis and (discr t or qualitativ) simulation purpos s.

Int r sting prop rti s of PI can   o tain d analytically using math matical prop rti s of qu uing n tworks. Qu stions such as av rag , minimum or maximum quantiti s of param t rs such as th waiting tim at qu u in a π-hu or th num   r of π-o j cts pr s nt at anytim in a π-hu or th ntir PI can   answ r d. Such answ rs can th n   utilis d   y algorithms that rout π-o j cts along th PI. Also, d sign of th PI n twork can   optimis d   y including for xampl t mporary storag in suita l parts of th n twork (π-storag) to smooth p rformanc .

Cost, tim , and r lia ility ar k y link p rformanc indicators from a shipp r's p rsp ctiv capturing th punctuality, tim and cost for transit from th factory (or oth r production sit) to th final custom r. P rformanc of th corridor for diff r nt typ s of shipm nt (.g. dom stic v rsus int rnational) n d to   consid r d and diff r nt corridors compar d on this   asis.

Th typ s of traffic along a corridor must also   consid r d. Although most corridors carry multimodal traffic, som ar configur d to carry sp cific typ s of traffic. A PI conn ct d corridor is xp ct d to   com mor multimodal as traffic nt rs and xits th corridor through diff r nt mod nod s (t rminals).

Financial charact ristics and p rformanc indicators such as th ratio of th cost of logistics to th valu of th d liv r d product, and th ratio of fr on   oard (FOB) to cost, insuranc , and fr ight (CIF) pric s.

[6] We call it an 'open' network because π-objects do not stay permanently in the PI but exit at the appropriate points (π-gateways, according to the PI nomenclature)

Non-financial Corridor M trics to consid r d includ :

- Th tim tak n to transit th whol corridor and ach part of it for th typ of goods consid r d (.g. fast moving, p risha l tc).
- Th cost to import rs or shipp rs to mov cargo ov r th l ngth of a corridor.
- Th fr qu ncy of s rvic s and th xp ct d wait tim for th whol corridor and ach of its compon nts
- R lia ility: Th variation in tim and cost for th whol corridor and ach part of its compon nts (r lia ility) could pot ntially impact d y oth quantitativ and qualitativ chang s to th transport patt rns.
- S curity& Saf ty: Th s curity of goods transport d in th corridor and th saf ty of th p opl involv d in that transport for th sam r asons as th oth r m trics a ov .

Link w ights can also us d to assimilat th ff cts of qu u s at nod s. For xampl , in mod lling road n tworks, th amount of traffic that can transv rs a traffic light int rs ction is m asur d through th notion of saturation flow. That is th num r of v hicl s that can xit th int rs ction in a hypoth tical hour of gr n light. Th sam int rs ction can also associat d to a trav l tim w ight, that r pr s nts th xp ct d tim loss at th traffic light. This conc pt is oft n us d to mod l qu u s, and at th sam tim simplify th r pr s ntation of th n twork.

Hu s conn ct multipl origins to multipl d stinations. Th y may also p rform additional functions to th cargo that pass s through th m. If incoming cargo is only transhipp d, th hu can consid r d to a transit or r lay hu . Int rmodal t rminal hu s ar th r for th int rfac tw n th diff r nt transport mod s and thus ar k y to acc ss int rmodal transport s rvic s and to nsur ffici nt and road-comp titiv int rmodal supply chains throughout urop .

B sid s th pur transhipm nt of loading units from on transport mod to th oth r, int rmodal t rminals und r PI hav to p rform s v ral asic functions such as:

- Trans-shipm nt of loading units tw n diff r nt transport mod s.
- Ch ck in/out functions, such as ch ck of import/ xport docum nts, th s curity and damag s to loading units, handling of dang rous goods and r sp ctiv docum ntation tc.
- Provision of transport m ans, such as rail ngin s and truck. Faciliti s such as cran s for loading and unloading of cargo.

Faciliti s for int rnal transhipm nts and t mporary storag of cargo.

In th Physical Int rn t, th N tworking Lay r compris s th int rconn ct d infrastructur of proc ssing, storag and transporting faciliti s (transport s rvic s, t rminals, distri ution c ntr s, war hous s) through which th goods will transport d from th ir origins (manufacturing, distri ution and oth r locations) towards th ir custom r(s) locations.

Conc ptually, th Physical Int rn t mploys an archit ctur similar to th digital Int rn t, with small r n tworks (similar to Int rn t's autonomous syst ms-AS) conn cting to ach oth r via gat way/rout rs (impl m nt d y th π-hu s) and forwarding (physical) pack ts of cargo from origins to d stinations.

Thus th Physical Int rn t protocols shar many charact ristics with th ir quival nt digital Int rn t protocols. For xampl , to rout physical pack ts (π-pack ts) through th Physical Int rn t, rout r nod s must mploy routing protocols similar to th Int rnal and Bord r gat way protocols.

Wh n pack ts ar rout d insid an autonomous syst m, any routing protocol pr f rr d y th administrator organisation can mploy d of cours . How v r, for pack ts that ar rout d outsid th oundari s of th autonomous syst m, sp cific gat way protocols must mploy d. Th s must agr d tw n all th int rconn ct d π-hu s. π-hu s must xchang routing information and synchronis with conn ct d π-hu s.

As discuss d in th pr vious s ctions, th PI f atur s and compl xity dictat , a compr h nsiv , y t as simplifi d as possi l n twork r pr s ntation. This is st achi v d through th consid ration of appropriat w ights, such as trav l tim , cong stion, fr qu ncy and r lia ility of s rvic s for PI Links. Th n a fictiv sourc and sink nod is assum d for v ry PI Hu , as illustrat d in Figur 5.5. This pproach allow for th additional r pr s ntation of within th PI hu op rations or prop rti s.

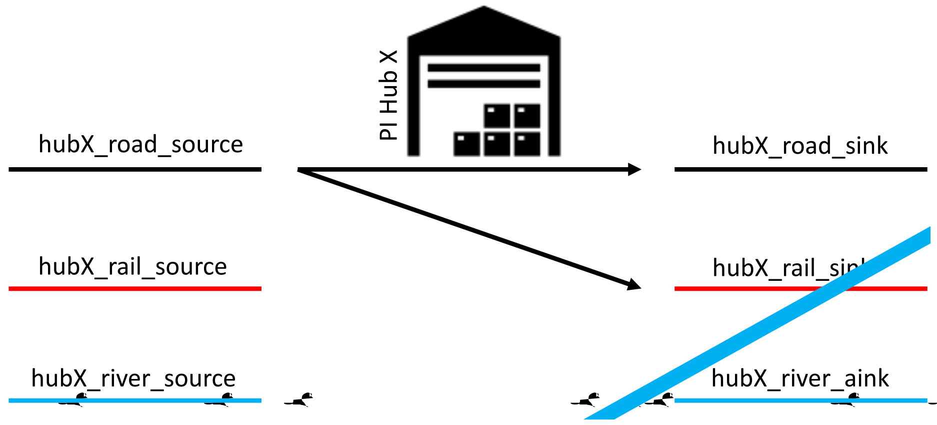


Figure 5.5: PI hub transhipment operations representation

In Figur 5.5 th transhipm nt op rations links that conn ct v ry arrival mod (sourc nod s), to v ry d partur mod (sink nod s) na l th assignm nt of w ights to PI Hu op rations. Transhipm nts can associat d to:

- Distanc s that r quir to cov r d. This w ight is mor r l vant to larg PI hu s such as th PoA wh r transhipm nt l gs ar of consid ra l distanc .
- Cost that can incorporat av rag handling cost
- Trav l tim that can incorporat av rag handling tim and qu u s
- Capacity that r pr s nts th num r of such transhipm nt PI hu infrastructur can und rtak .

A similar n twork r pr s ntation can adopt d for capturing PI hu sp cific costs and f atur s, such as local cong stion, qu u s at customs, various rout s and th ir capaciti s, storag capa ility, cross-docking faciliti s.

5.1.2 Data Structure

With th n twork r pr s ntation of th PI pr s nt d in th pr vious s ction including a vari ty of w ights and op rations r pr s ntation, it r quir s to associat d to a similarly compr h nsiv data structur . This data structur uilds on th data structur provid d y th GPICs and d scri d in S ction 2.3 of this r port. Following th graph th or tic approach to th r pr s ntation of n tworks, th data structur r quir s to consid r PI Nod s and PI Links and th ir prop rti s. Additionally, as th

PI, approach s th transportation of cargo as data pack ts, it r quir s an additional l m nt that is not pr s nt in digital n tworks, that of PI mov rs. PI mov rs ar th rolling stock availa l in th Physical Int rn t on which PI contain rs, th PI cargo, ar transport d. B ing an int gral part of th PI, PI mov rs and th ir prop rti s also r quir to   consid r d in a data structur d finition.

Anoth r p rsp ctiv of th PI n tworks data structur is that of data d tail. A n twork of nod s and links can   accurat ly r pr s nt d as a static n twork. Such r pr s ntation focus s on th strat gic infrastructur   d v lop d that form th n twork. Such infrastructur ar road/ highways, rail and riv r ways, int rmodal t rminals and v n fr ight handling airports. Such infrastructur has fix d location, and d sign prop rti s (.g. num r of rail tracks, road lan s, war hous ar a) that can   associat d to static prop rti s.

For op rational l v l n twork r pr s ntation mor dynamic prop rti s r quir to   consid r d. As discuss d in th pr vious s ction, qu u s ar a typical issu in logistical chains. R gardl ss of w ath r a qu u will   r pr s nt d as an int g r num r of qu u ing it ms or as an xp ct d trav l tim on a link, this is a dynamic prop rty that fr qu ntly r quir s updating. Road mapping s rvic s, typically off r liv cong stion information, and y using th link trav l tim r pr s ntation, can stimat th accumulat d impact of qu u s, on any rout .

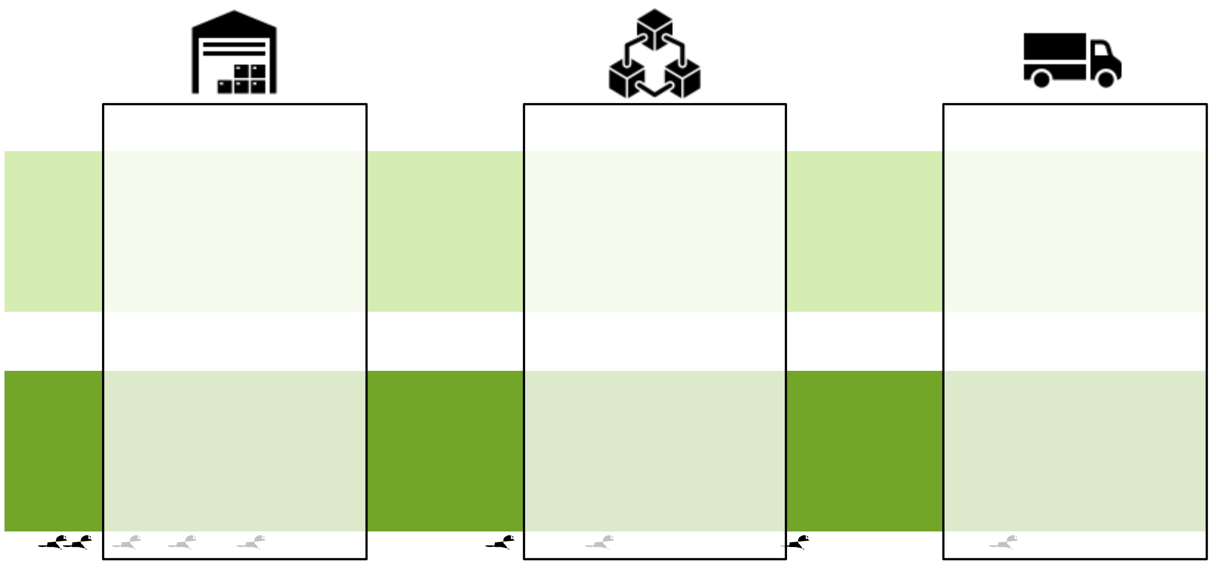


Figure 5.6: PI data structure classification

Th r for , th PI n twork data structur consid rs data for nod s, links and mov rs, involving oth th ir static prop rti s and th ir dynamic status. As illustrat d in Figur 5.6, th data mod l aligns with th GPICS d finitions, ut also functions as an op n nd d consolidat d information s rvic , wh r   v ry us r can pot ntially id ntify r l vant and us ful information for routing and synchro-modality d cision making.

For PI Nod s static data involv th location, th int rmodal conn ctivity, th war housing capa ility/ capacity and th functions (.g. int rmodal, cross-docking). Dynamic information includ th spar war hous capacity and th qu u information p r s rvic provid d. Additional information on w ath r might also   r l vant in cas a PI Ord r involv s w ath r conditions in th conditions of carriag .

For PI Links th static data includ th origin and d stination nod s locations and IDs, th mod , th functions (.g. r frig ration capa ility), th rid quality (umpin ss) and th distanc . It may th cas that th r ar two or mor links tw n th sam origin and d stination if mor than on mod s ar availa l . S v ral dynamic w ights can associat d to PI Links including:

- Cost, that may simply consid r th link l ngth and th p r km cost of th link's mod . Additional d tail can add d to account for staffing costs (.g. driv r) in associationg to trav l tim transport mode and service within each network path must be considered and analysed. Additional constraints posed by the shipping instruction such as time windows, must be taken under consideration also of network characteristics such as capacity limitations of hubs and distribution centres, preferred carriers, and so on. In order to achieve an optimal planning solution, a transportation planning manager therefore must balance the different requirements and constraints with the availability options.

The transportation planner deals with the short-term/ operational functionality of the networking layer and acts upon a shipping instruction received by the shipper. The transportation planner will analyse the shipping instruction and decide on the best way to forward it through PI by considering the available and feasible network options. The transportation planner needs to work with the shipper, the carrier who will transport the goods (at least to the initial PI hub) and also possibly with the terminals/hubs themselves.

Pricing, timing, capacities, and quality of service drive the decision of what modes and routes the transport planner will consider use. PI Links and Hub rates (costs), capacity, and associated efficiencies (time and service levels) will determine the competitiveness of each corridor. Issues like congestion and backhauling must also be taken into account.

5.2 Networking Service Protocol

To accommodate the dual functionality of the Networking Service, it is divided into two separate stages.

- Stage 1 deals with the collection and integration of PI network information, and
- Stage 2 deals with the provision of PI Shipment specific information.

5.2.1 Network discovery module

In order to identify the relevant nodes and links of the network(s) in collaboration with the Link and Physical Layers, the Networking service Stage 1 classifies them in terms of geographical location (and scale), transport mode, and level of aggregation as proposed by the GPICS PI Node and PI Link typology.

The standardised classification of the PI components enables the interoperability across various services and systems that communicate with the Networking Service. Data are refreshed depending on their nature (static, dynamic, live) at different frequencies. For example static data, that capture infrastructure changes (new roads, new ports. Hubs) are updated every few days. Dynamic data such as weather conditions, road works, or truck fill rates are updated every few hours. Finally, live data, that concern travel times, queues and congestion are updated every few minutes.

The Networking Service seeks the required data from various data sources as illustrated in **Figure 5.7**. At the same time, it collects and analyses the data from ICONET IoT platform to cross-check information. Finally, it holds a database of historical weight values, that it uses to make short term predictions for weights such as PI Link consolidation rate. This capability can be useful in helping the transport planner tool or the routing service to make enhanced and more complex routing decisions.

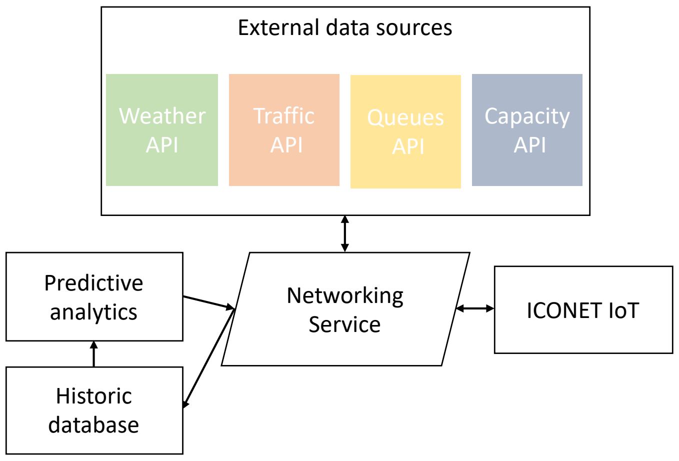


Figure 5.7: Networking service network discovery (Stage 1)

5.2.2 Data packaging module

Networking Service Stage 2 aim to pack information relevant to a specific PI Order. This module is of little value when the datasets are small, but it becomes increasingly useful as the PI grows in scale and detail. The data structure presented in this Chapter is utilized throughout the application of the Area, Modes, Aggregation level and Data detail tools, which are described as follows:

The aim of the geographical scale function (Area tool) is to limit the scope of the search area for network components. An area of relevance is identified on the global map, for the specific PI shipment submitted. For example, the scale will be different for a request to carry a cargo from North to South Europe, or between two neighbouring French cities. The Area tool utilizes the origin and destination coordinates of the PI shipment to identify an oval shaped area of relevant PI network components.

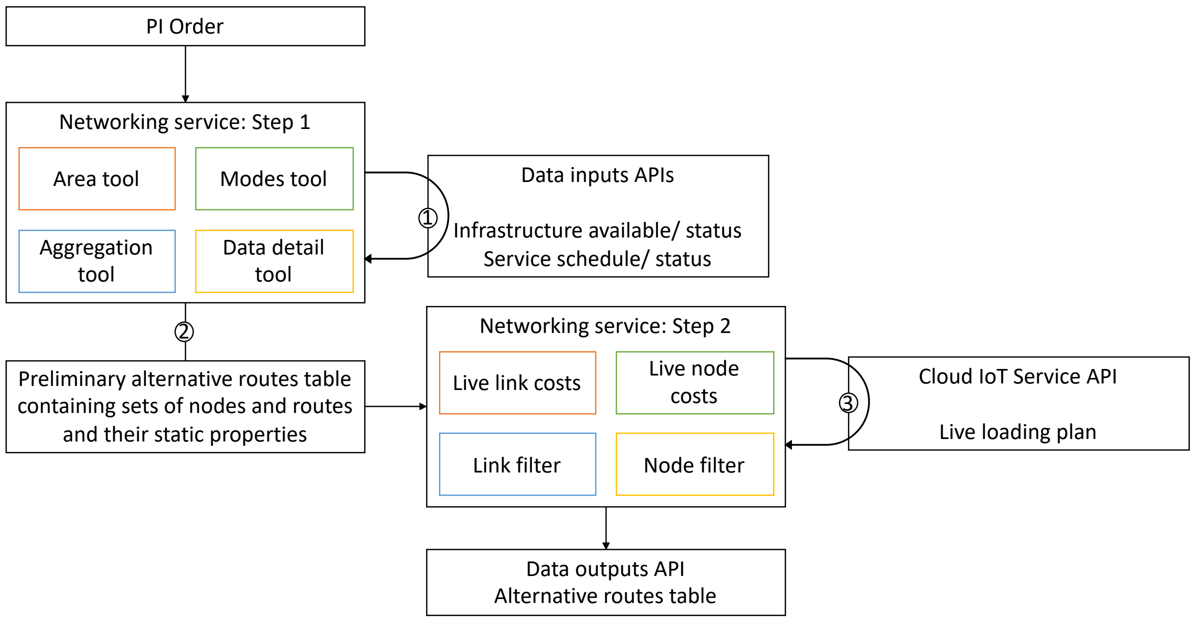


Figure 5.8: Interactions of Networking Service data packaging tool

Th mod tool consid rs r strictions impos d   y   ach PI ord r on th   mod s availa l   for shipm nt. If mor   than on   mod s ar   f asi l , th   N tworking S rvic   ass ss th   multimodality options availa l ,   y consid ring transhipm nt nod s and various mod   links.

Th   aggr gation tool consid rs th   l v l of d tail r quir d for th   routing r qu st associat d to a sp cific PI ord r. PI nod s can r pr s nt int rnational or local hu s in th   cas   of long-haul shipm nts, local war hous s and postcod s in th   cas   of   -comm rc , as w ll as sp cific function (.g. customs) in compl x port (intra-hu) op rations.

With awar n ss on th   scal , aggr gation l v l and mod s a final d cision is mad   on th   l v l of data d tail r quir d. This will d p nd on th   PI ord r mad ,   ut also on data availa ility. Th   output data d tail can rang   from physical prop rti s of infrastructur , to liv   information on th   s rvic s op rating on th   PI n twork. Four l v ls of data d tails can   id ntifi d:

- Infrastructur   prop rti s: N twork information d scri   static infrastructur   charact ristics such as th   l ngth of a link, th   mod s that can accommodat   th   function of carrying cargo (.g. truck, rail), or   v n mor   d tail d information such as classification into motorway, or num   r of lan s. A similar conc pt can   appli d to th   d scription of nod s. A nod   can r pr s nt a war hous   that has sp cific capacity for storag   and docking capa ility.
-

Th final output of th n tworking s rvic is a s t of int rconn ct d PI nod s, PI links and PI s rvic s, that ar availa l for transporting a shipm nt tw n any two nod s. Stag 1 of th N tworking S rvic that is r sponsi l for coll cting information on th status of th n twork, is always list ning for chang s in traffic or s rvic s status. D p nding on th natur of th PI Ord r th N tworking S rvic Stag 2 can   ith r call d onc or s v ral tim s. For cas s that only static information ar availa l th N tworking S rvic is call d only wh n an ord r is initiat d, whil for cas s that information is dynamically updat d, it is call d wh n v r a shipm nt arriv s at a PI nod that it is not th d stination. **Figure 5.8**, captur s th op rational s qu nc for Stag 2 of th N tworking S rvic .

5.2.3 Optimal fulfilment store assignment to orders

In th cont xt of ur an d liv ry, it is oft n th cas that th d stination and tim slot of an ord r is known, ut th r is no giv n ord r fulfilm nt origin. To incorporat   ur an Comm rc d liv ry into th conc pt of th Physical Int rn t, an fulfilm nt c ntr id ntification tool has   n incorporat d into th N tworking S rvic .

Th aim of th tool is to associat ord rs with unknown fulfilm nt locations to optimal origin locations. This is handl d through a lin ar optimisation mod l that s ks to minimis th total distanc for satisfying all ord rs. Assuming that th known distanc d_{ij} tw n v ry custom r location j and v ry fulfilm nt stor i, and that an additional int g r varia l s_{ik} captur s th stock of products availa l at ach fulfillm nt stor i p r product k. And an additional int g r varia l o_{jk} captur s th num r of products of product k ord r d in ord r j. A inary d cision varia l x_{ij} is qual to 1 if fulfillm nt stor i is chos n to satisfy custom r ord r j, and is 0 oth rwis . Th n, a cost minimization pro l m can   formulat d as follows:

O j ctiv function:

$$\min_{x_{ij}} \sum x_{ij} d_{ij}$$

Su j ct to constraints:

$$\sum_{i} x_{ij} \geq 1 \quad \forall j, k$$

$$\sum_{j} x_{ij} * o_{jk} \leq s_{ik} \quad \forall i, k$$

$$x_{ij} \in \{0,1\}$$

Th first constraint nsur s that all ord rs ar satisfi d. Th s cond constraint nsur s that th stor capacity for ach SKU is not xc d d, whil th last constraint d fin s th possi l valu s for th d cision varia l s.

5.3 Service sample application and design guidelines

N tworking is th group of proc ss s and activiti s that analys th availa l n twork options for transporting th goods to th d stination, according to th shipping instruction.

5.3.1 TEN-T PI Network

In th cont xt of th North-South urop an corridor Living La , th N tworking S rvic function is to und rtak th n twork discov ry and shar th information with oth r s rvic s. Th n twork illustrat d in **Figure 5.9**, r pr s nts th nod s of th T N T n twork (gr n points) and th P&G war hous locations (r d points). PI Links of road, rail, and riv r mod s ar consid r d tw n PI Nod s, and a road link is introduc d tw n v ry P&G war hous and its clos st PI Nod . S a links ar consid r d for th PI Nod s that ar not acc ssi l oth rwis (.g. Cyprus).

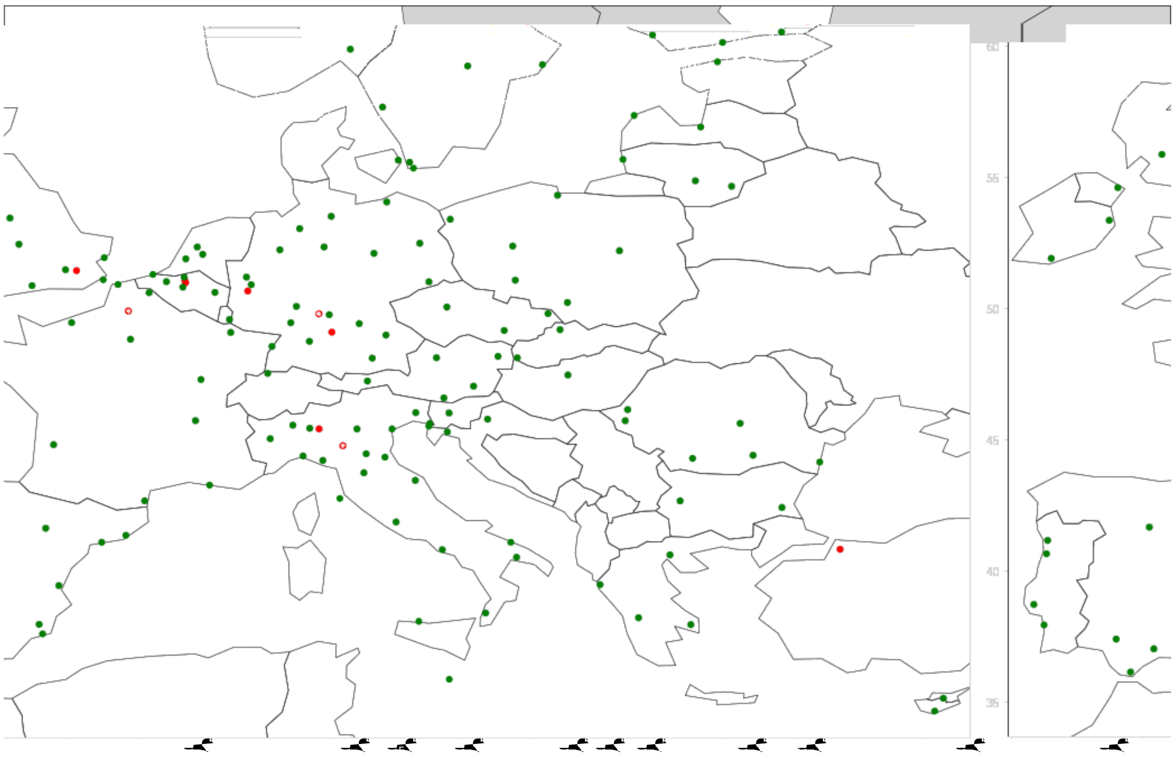


Figure 5.9: North-South Europe PI Corridor

Although P&G do s not consid r p nalti s for lat d liv ry of th ir Ti r 1 (high urg ncy) shipm nts, it has ask d fr ight forward rs to provid s parat rat s for 5% xpr ss d liv ry, or rat s including 5% xpr ss. Th PI should th r for   a l to provid customiz d d liv ry f atur s with r sp ct to th sp d of d liv ry. For xampl urg nt, low cost, lost missions.

linkid	linkorigin	linkdestination	originid	destinationid	linkmode	costeuro	distkm	traveltimemins
0	Lefkosia	Limassol	148	147	Road	127	84.0	60
1	Limassol	Athens	147	145	Sea	48	972.3	2100
2	Athens	Patras	145	146	Road	319	210.0	141
3	Athens	Patras	145	146	Rail	48	210.0	157
4	Athens	Thessaloniki	145	143	Road	761	501.0	305

Figure 5.10: TENT PI Links and their weights

By adopting th multipl w ight data structur illustrat d in **Figure 5.10**, information on th distanc , cost, and trav l tim can   r tri v d   y routing s rvic s for calculating th optimal rout to th d stination. Th optimal rout id ntifi d chang s as diff r nt w ights ar consid r d. Furth rmor , th w ights can   customis d p r custom r n ds, as in th cas of P&G to d liv r cargo with diff r nt priority.

5.3.2 eCommerce

In th cont xt of Comm rc and ur an d liv ri s, th information r quir d for th shipm nt of cargo diff r wh n compar d to th g n ric PI cas of long haul shipm nts. To account for this uniqu f atur of Comm rc , th d scription of PI Nod s has n xt nd d to accommodat product stock l v ls as illustrat d in **Figure 5.11**. Op rating hours and picking capacity ar consid r d as s rvic prop rti s, that ar also d fin d in g n ric PI Nod s. This r pr s ntation na l s th id ntification of shipm nt origins if this is not known, as discuss d in S ction 5.2.3, wh r custom r ord rs w r associat d optimally to ord r fulfilm nt stor s.

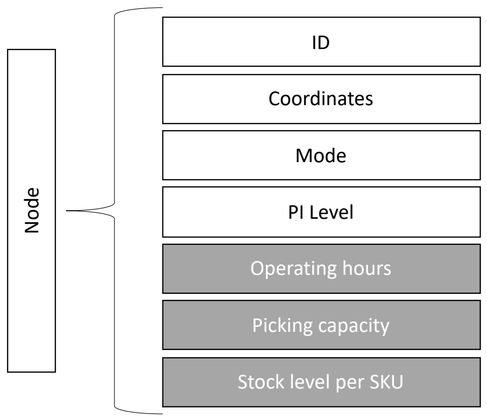


Figure 5.11: eCommerce PI Node information structure

5.3.3 Design guidelines

To d v lop st-practic guid lin s th nd-to- nd proc ss of th N tworking S rvic in th cont xt of ach Living La is xamin d. With ach LL off ring a su stantially uniqu point of vi w into th Physical Int rn t, N tworking S rvic ar propos d for addr ssing th d sign r quir m nts in ach Living La .

In th cont xt of a PI Hu th PI N tworking S rvic consid rs a n twork that spans from th arrival and d partur t rminals off r d y ach mod (s a int rnational and int rcontin ntal trad , road, rail riv r conn ctions to hint rland). In t rms of n twork r pr s ntation aggr gation, th PI n tworking s rvic captur s port and r gional int rmodal hu s, ut also port s rvic s that cargo n ds to trav rs , such as customs, or port stack capacity. Such artificial nod s ar associat d with throughput rat s or throughput capacity, that ar fr qu ntly th caus of port cong stion and qu u s. Additional routing options within th port ar xplicitly r pr s nt d y Links. Th data includ oth th static prop rti s and dynamic op rational status information of th n twork, consid ring int rmodal capa ility wh r availa l . Localis d failur s or cong stion ar anticipat d to inform and trigg r cargo r -routing options. Such a n tworking s rvic na l s, th PI to provid nhanc d modal choic s that align with th hu 's infrastructural capa ility. Furth rmor , it has a long-lasting ff ct on th ffici nt utilization of port capacity and facilitat s.

C

Th N tworking S rvic d sign for PI Corridors spans g ographically across th urop an contin nt providing s v ral north-south corridors. Th T N-T n twork nod s (L v l 1 GPICS) ar consid r d as inflow or outflow points, as w ll as points of consolidation or transhipm nt provid d suffici nt infrastructur is in plac . Th mod s s rving adjac nt links captur not only for road, rail and riv r that str tch inland, ut also for s a links such as Norway-Finland and Italy-Gr c . Consid ring th scal of th n twork, aggr gation focus s on th city nod s and links of th n twork. ach nod is associat d with a c rtain l v l of production and consumption. For int rmodal nod s, throughput capacity of intramodality is also consid r d. To na l synchro-modality and cargo consolidation at nod s, data cov ring infrastructur prop rti s, status, as w ll as s rvic s sch dul and loading status ar maintain d. This na l s th PI Corridor, to achi v high r utilisation rat s of infrastructur and s rvic s.

G

In Comm rc th distri ution n twork is typically op rat d y Logistic S rvic Provid rs. In such cas s, int rmodal transhipm nt options ar not consid r d. N twork aggr gation consid rs th capacity of ach r gional stor to accommodat conting ncy stock and th capacity of ach v hicl to consolidat d liv ri s, in th s ns that it can pick up a conting ncy stock along th way to satisfy d mand at an outl t approaching stock-out. Th n tworking s rvic optimal fulfilm nt stor id ntification modul is also d ploy d, if only l ss sophisticat d approach s ar in plac . To achi v consolidation of shipm nts, a t mporal r pr s ntation of v hicl loading capacity availa ility is maintain d as d on dynamic s rvic loading data.

Scal -wis th War hous as a S rvic (WaaS) focus s on th r gion th sp cific provid rs faciliti s cov r. This is typically national, h nc a national scal mod l, that also consid rs national points of cargo ntry and xit is consid r d. As oth rail and road links ar consid r d, national ntry and xit points should also account for Franc int rnational rail fr ight hu s. With faciliti s and custom rs spr ad all across th cov rag r gion, a d tail d n twork of links, suppl m nting th T N-T n twork is maintain d, capturing th distanc s tw n all war hous s, as w ll as custom r pick-up and d liv ry locations. WaaS nod s ar r pr s nt d at highly disaggr gat l v l, to incorporat war hous proc ss s for incoming and outgoing storag , as w ll as cross-docking s rvic s. Data-wis th prop rti s, s rvic s and storag availa ility status of ach war hous is maintain d.

Th d sign r comm ndations mad for ach Living La cont xt ar summariz d in Figur 5.12.

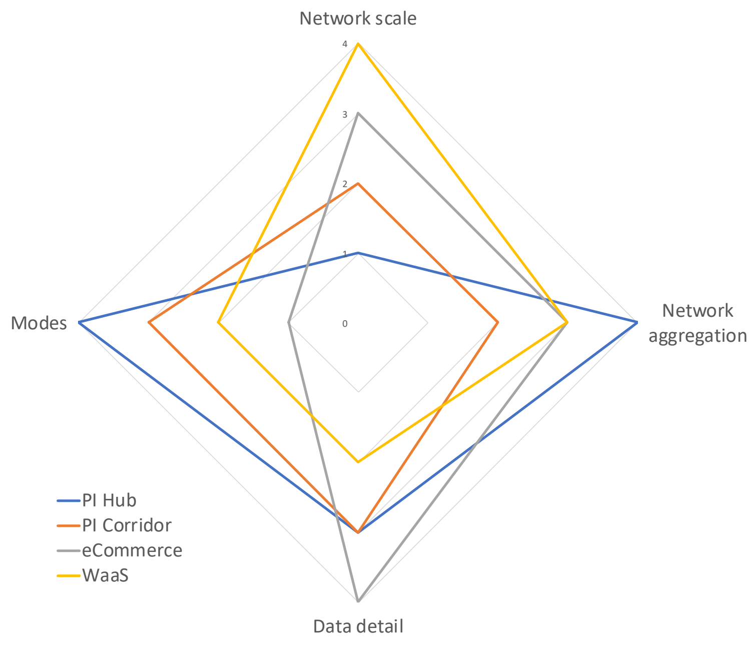


Figure 5.12: PI Networking design recommendations

6 ROUTING SERVICE

This s ction r ports on th approach adopt d for PI routing s rvic of ICONET. Th routing s rvic uilds upon th routing algorithm propos d in first and s cond v rsions of this d liv ra l (D2.3 & D2.4). Th o j ctiv of routing s rvic is to find th st path tw n two PI-Hu s consid ring trav l tim , distanc and CO2 mission costs for a giv n s t of constraints. Th pr vious v rsion (D2.4) of this d liv ra l , formulat d th routing s rvic as V hicl Routing Pro l m (VRP) and Trav lling Sal sman Pro l m (TSP) with som modifications to consid r th asp cts of th PI such as int rmodal transportation and r al tim chang s in th PI n twork. In this d liv ra l , w additionally r port on advanc m nts mad in impl m nting th solutions for VRP/TSP. Not TSP is su s t of VRP and d als with on rout wh n as VRP can handl multipl rout s. Trav lling Sal sman pro l ms (TSP) and its mor g n ric form V hicl Routing Pro l ms (VRP) ar classic com inatorial (NP-hard) pro l ms in op rations r s arch (OR) and th s ar formulat d as int g r constrain d optimization, i. . with int gral or inary d cision varia l s. Th th ory and algorithm d sign communiti s hav typically us d graphs to formulat th s pro l ms. Classically, approach s to tackling an optimization pro l m can cat goriz d into xact, approximation, and h uristic algorithms. xact algorithms ar as d on num ration or ranch-and- ound with an int g r programming formulation and th y guarant to find optimal solutions ut ar not f asi l for larg instanc s. On th oth r hand, polynomial tim approximation algorithms ar tracta l for larg instanc s, ut may suff r from w ak optimality guarant s or mpirical p rformanc . Finally, h uristics ar fast and ff ctiv algorithms ut r quir pro l m-sp cific knowl dg and manual d sign of math matical mod l for th solution.

To r duc th ffort of manual math matical mod lling for solutions to OR pro l ms optimization, r s arch rs hav r c ntly, sp cially aft r th s minal work of Point r N tworks (Vinyals t al., 2015), start d looking at machin l arning and r inforc m nt l arning as d approach s (Kool t al., 2019; Nazari t al., 2018; B ngio t al., 2018; Khalil t al., 2017; B llo t al., 2016). Th l arning as d m thods ar train d on larg num r of pro l m instanc s, and hav n shown to xtr m ly fast in producing solutions of r asona ly good quality. How v r, wh n compar d with th sam nchmark instanc s, th s l arning- as d m thods cannot outp rform th stat -of- th -art m thod LKH3 (H lsgaun, 2017), which is a p nalty-function- as d xt nsion of classical Lin-K rnighan h uristic (Lin & K rnighan, 1973).

In th ICON T proj ct, w att mpt to com in th a ility to s arch for accurat solution y h uristic algorithms with th a ility of machin l arning to l arn from larg num r of instanc s. In particular, w com in th str ngths of oth worlds in a fram work whil k ping th focus on int rmodal and dynamic asp cts of th PI. Th r for , w propos an nd-to- nd fram work that l arns solution dynamically in an it rativ fashion inst ad of dir ctly constructing a solution to a TSP/VRP instanc . This is as d on th approach known as *neural combinatorial optimization* propos d y B ngio t al., 2018.

- W pr s nt a nov l modular fram work wh r inst ad of all op rators of a solution in on algorithm, it com in s plugga l modul s to l arn an approximat solution dir ctly from th pro l m instanc .
- Th fram work can l arn approximat solution form a hug num r of pro l m instanc s in a much fast r way than th h uristic m thods whil optimal solution is d riv d via sup rvis d or r inforc m nt l arning.

- L arning is as d on Graph N ural N tworks (GNN) wh r w r pr s nt nod s and links in m dding spac through convolutions lay rs in a t mporal fashion to captur th dynamic chang s in th PI n twork.

6.1 Routing Service Considerations and Design

In th pr vious v rsion of this r pot (D2.4) a d tail d d scription of th approach to mod lling th PI N twork mov m nts and d ploying th V hicl Routing Pro l m as w ll as its variants w r discuss d into d tail. This s ction focus s on computational compl xity and solution algorithms for routing pro l ms.

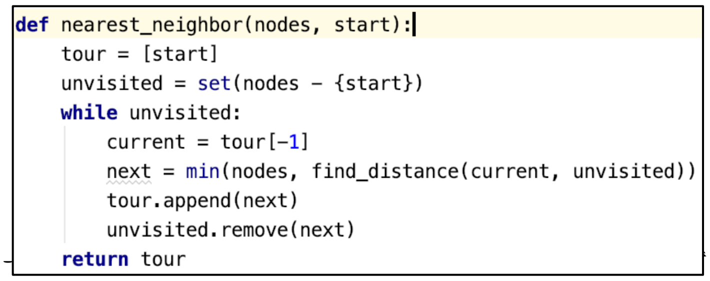
6.1.1 Computational complexity of optimal routing algorithms

Du to th larg scal and num r of compon nts participating in th Physical Int rn t, in th following s ctions, w inv stigat th tracka ility and compl xity of routing computation algorithms. H uristic and l arning as d routing solutions ar inv stigat d that hav   n impl m nt d and/or adapt d for th LL sc narios in th ICON T proj ct

Simpl st algorithm which guarant s th solution TSP pro l m is y g n rating all possi l tours of th nod s in th graph and choos th short st tour. How v r, such an algorithms is not f asi l for larg num r of nod s. Th r ason ing th larg num r of nod p rmutations that n d to xhaust d   for finding a com ination of nod s with minimum path l ngth. This can   xplain d y a simpl calculation. L t's assum , it tak s 2 s conds to d t rmin a TSP tour as solution for visiting 10 nod s; i. . xact algorithm will hav to go through 10! possi iliti s to find   st solution in t rms of minimum path l ngth. Now if on mor nod ar add d th n on sam computing machin it will r quir $2\,secs \times 11!\,/\,10! \approx 22\,secs$. Adding on mor nod will r quir $2\,secs \times 12!\,/10! \approx 4\,mins$. And for n=14 tim compl xity incr as s to $2\,secs \times 14!\,/\,10! \approx 13\,hours$, for $n = 18$ it will tak $2\,secs \times 18!\,/\,10! \approx 112\,years$ and so on. It is vid nt from th s simpl calculations why finding xact solutions ar not f asi l for TSP. This r quir s approximation of th   xact solution. In oth r words, w find th path with minimum distanc   ut algorithm do s not guarant   if th solution is th only short st. Th following s ctions giv d tails for som of th h uristic approximation algorithms, w us d to solv TSP rout in th ICON T proj ct.

A

N ar st n igh our (NN) algorithm starts from an ar itrary initial nod and r p at dly choos s n xt unvisit d nod . Th final tour g ts xt nd d at ach st p y including a n ar st unvisit d nod and finally r turn to start nod .



```
def nearest_neighbor(nodes, start):
    tour = [start]
    unvisited = set(nodes - {start})
    while unvisited:
        current = tour[-1]
        next = min(nodes, find_distance(current, unvisited))
        tour.append(next)
        unvisited.remove(next)
    return tour
```

Figure 6.1: Nearest neighbour algorithm

In ord r to d t rmin st NN algorithm for a giv n pro l m, w can compar p rformanc of NN y using ach of th nod s in th graph as start nod and d t rmin th optimal start point. To compar NN p rformanc w d t rmin d th optimality gap for NN from xact algorithm. This is achi v d y d t rmining th ratio of tour l ngth found y NN with tour l ngth from th xact algorithm:

$$Optimality\_Gap = \frac{TourLength_{NN}}{Tourlength_{EXACT}}$$

G n rally, d sign of h uristic algorithms may consist of on or mor of th following options:

1. Tour construction algorithms
2. Tour improv m nt algorithms
3. ns m l algorithms

So far w hav construct d th tour with NN algorithm. In ord r to furth r optimiz th solution, w adopt a strat gy to improv th solution. On strat gy is th *repetition strategy* und r which algorithm is r -run multipl tim s varying som asp cts (such as start nod in our NN algorithm cas) and solution with st scor is s l ct d as optimal solution. S cond strat gy is *alteration strategy* wh r initial construct d tour is furth r improv d y making chang s.

On such improv m nt algorithm is *2-opt* algorithm: Start with a giv n tour. R plac 2 links of th tour with 2 oth r links in such a way that th n w tour l ngth is short r. Continu in this way until no mor improv m nts ar possi l . On of th most ff ctiv approximat algorithms for TSP is *Lin-Kernighan (LKH)* which adopts *k-opt* strat gy for improv m nt. Finally, tour construction and tour improv m nt algorithms can com in d in an ns m l strat gy which w adopt in d signing our algorithms for routing s rvic in th ICON T proj ct.

On of th shortcomings of NN algorithm is if th r ar outli rs in th data. For xampl , in a sc nario wh r on location/city to visit d is far away from r st of th citi s. In such cas NN algorithm will visit citi s which ar clos to ach oth r for visiting th city which is outli r. In this cas , th r is ov rh ad in visiting outli r locations. To addr ss this, w d t rmin final tour y r v rsing th s gm nts wh r a s gm nt is a s qu nc of cons cutiv citi s within a tour. A s gm nt is op n- nd d and do s not hav loop. So if [A, B, C, D] is a tour th n on of th s gm nts com inations d fining this tour can includ [A, B, C], [C, D]. In th impl m ntation, w r v rs only if it d cr as s th path l ngth.

Table 6.2 Comparison of optimization strategies for NN

Method	$N = 10$		$N = 20$		$N = 50$		$N = 100$	
	Avg. Tour Length	**Time**	**Tour length**	**Time**	**Tour length**	**Time**	**Tour length**	**Time**
NN	2381.4	0.00s	3363.5	0.00s	5039.5	0.00s	6734.1	0.001s
NN R p tition Strat gy	2297.7	0.00s	3218.8	0.001	4511.7	0.018s	5912.6	0.118s
NN 2-opt strat gy	2333.4	0.00s	3076.8	0.001s	4408.8	0.003s	5909.5	0.018s
NN ns m l strat gy (R p tition + 2-opt)	2291.8	0.002s	3022.1	0.015s	4169.1	0.094s	5701.6	0.364s

First of all, w notic in Ta l 6.1 that xact algorithm is not a l to comput a solution for a graph with n>=14 in a r asona l tim . In Ta l 6.2, w s that for w ar a l to find solutions for larg r TSP instanc s. In ord r to s th diff r nc tw n oth algorithms, w point r ad r to a ov ta l s wh n n=10. For n=10 xact algorithms find solution with short r l ngth ut in plain NN cas algorithms is fast r, ut it did not find short st tour. Th optimality gap for n=10 ov r 10 training sampl s is giv n low:

```
[1.0,
 1.0786730882270583,
 1.1183939455269463,
 1.122045907779504,
 1.1420044596384102,
 1.1574244508712004,
 1.1597961299811668,
 1.1816006960584013,
 1.2178138989487983,
 1.2643343323299288,
 1.3425992274378575]
```

Figure 6.4: Optimality gap

Th ratio of 1.0 m ans NN and xact algorithms got th sam (optimal) r sult; that happ n d just onc tim s out of 10. Th oth r tim s, w s that th NN produc s a long r tour, y anything up to 34% wors , with a m dian of 1% wors .

Wh n NN compar d with its variants with diff r nt r p tition and alt ration strat gi s, w s in Ta l 6.2 that NN with r p tition strat gy p rforms tt r than th vanilla NN and clos to xact algorithm. In ord r to d t rmin th num r of r p titions r quir d to find st solution, w run th algorithm for 30 instanc s with 60 to 150 starting nod s wh r optimal tour is d t rmin d ov r a rang of 0 to 100 r p titions, W r cord av rag , min, max of tour l ngth and th ir standard d viations from th m an.

Table 6.3: Benchmarking for starting nodes and repetitions

NN variants	**Mean**	**Min**	**Max**	**Std. deviation**	**Time per tour**
NN (r ps=0)	7195	6315	8180	441	0.001s
NN (r ps=10)	6753	6325	7529	336	0.011
NN (r ps=20)	6673	6238	7462	289	0.019
NN (r ps=50)	6595	6223	7243	255	0.047
NN (r ps=100)	6575	6213	7243	259	0.086

From Ta l 6.3, it is cl ar that NN algorithm r sults in short r av rag tour l ngth ut w start g tting diminishing r turns aft r 50 r p titions. It will d p nd on th us cas prioriti s (run tim v rsus tour l ngth), som wh r around 25 or 50 r p titions might a good trad -off.

In addition to NN and NN with r p tition, Ta l 6.2 shows th r sults from NN with alt ration and ns m l strat gi s and w s that av rag tour l ngth short ns with ns m l strat gy ut run tim incr as . So d p nding on th LL's sc nario, w will adopt strat gy accordingly in th ICON T proj ct.

6.2 Routing Service Protocol

6.2.1 Service Design

D

D p L arning mod ls hav l d qualitativ r akthroughs with uclid an data such imag , t xt and sp ch for a wid vari ty of tasks such as sp ch r cognition, machin translation and imag analysis. Convolutional n ural n tworks (L Cun t al., 1998) ar g n ric uilding locks for d p l arning archit ctur s for Comput r Vision and NLP tasks, ut ConvN ts r quir r gular data such as 2D and 3D grids for comput r vision and 1D t xt s qu nc for NLP. How v r, in com inatorial optimization pro l ms, r al-world data has irr gular structur and is non- uclid an. Supply chain n tworks, transport n tworks, and s nsor n tworks ar xampl s of non- uclid an data structur and can mod ll d as graphs.

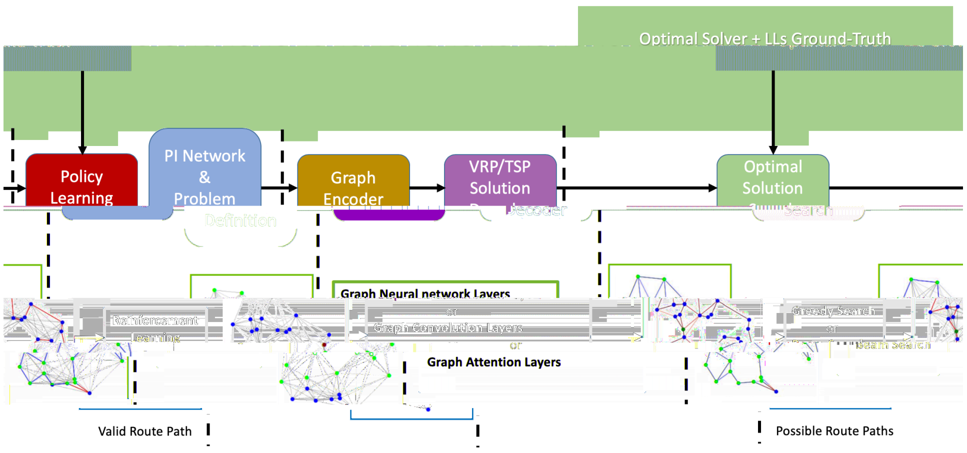


Figure 6.5: Deep Learning based Routing Framework

On of th sp cial cas s of VRP is wh n th r is only on v hicl und r consid ration. Such sc nario can imagin d wh n routing PI-Contain rs that hav sam d stination and rout optimization is r quir d y PI-mov r transporting thos contain rs. This simpl cas of VRP is Trav lling Sal sman Pro l m and in this d liv ra l , w formulat VRP or TSP as a l arning pro l m on graphs. Formally, giv n a fully conn ct d PI graph of n PI-Hu s in two dim nsional unit squar $S = \{x_i\}_{i=1}^{n}$ wh r ach $x_i \in [0,1]^2$, th o j ctiv is to l arn a p rmutation of th nod s p as a tour that visits ach nod onc and has minimum total l ngth, d fin d as:

$$L(p \mid s) = ||x_{p_n} - x_{p_1}||_2 + \sum_{i=1}^{n-1} ||x_{p_i} - x_{p_{i+1}}||_2$$

wh r $\|.\|_2$ d not s l_2 norm.

A graph n ural n twork (GNN) ncod r comput s d-dim nsional r pr s ntation of nod s (PI-Hu s in ICON T) in th graph (PI-N twork in ICON T). In its most asic form, an ncod r is a function that maps a nod dir ctly into a v ctor spac . Formally, th ncod r is a function, $ENC : V \to \mathbb{R}^d$, that maps nod s to v ctor m ddings, $z_i \in \mathbb{R}^d$ (wh r z_i corr sponds to th m dding for nod $v_i \in V$). Th stat -of-th -art m thods that mploy such ncoding t chniqu s ar as d on d p n ural n twork archit ctur s and hav shown st p rformanc in link pr dictions tasks (Hamilton t al., 2017a; Kipf and W lling, 2017; Pham t al., 2017). At ach lay r of th GNN, nod s aggr gat f atur s from th ir n igh ouring nod s to r pr s nt local graph structur via r cursiv m ssag passing (Gilm r t al., 2017). With th m ssag passing sch m nod and dg f atur s at lay r $\ell + 1$ can r pr s nt d in t rms of nod f atur s (h^ℓ) and dg f atur s (e^ℓ) at lay r through lin ar transformation as:

$$h_i^{\ell+1} = h_i^\ell + f\left(\mathrm{BN}\left(U^\ell h_i^\ell + \mathrm{AGGR}_{j \in \mathcal{N}_i}\left(\sigma(e_{ij}^\ell) \odot V^\ell h_j^\ell\right)\right)\right)$$

$$e_{ij}^{\ell+1} = e_{ij}^\ell + f\left(\mathrm{BN}\left(A^\ell e_{ij}^\ell + B^\ell h_i^\ell + C^\ell h_j^\ell\right)\right)$$

BN is BatchNorm (Ioff &Sz g dy, 2015) normalization, AGGR is n igh orhood aggr gation function such as SUM, M AN or MAX. f is activation function such as R LU, σ is th sigmoid function, and $A^\ell, B^\ell, C^\ell, W^\ell \in \mathbb{R}^{d \times d}$ ar l arna l param t rs. In ICON T, w adapt ncod rs as d on two diff r nt d p l arning archit ctur s.

E G

H r , w giv th d tails of Graph Convolution n twork (GCN) archit ctur adapt d as ncod r for ICO NT's PI graph. As input lay r to GCN, w conv rt two dim nsional coordinat s of PI-hu s to h-dim nsional nod and dg inputs for n nod s and n^2 dg s r sp ctiv ly. Th nod inputs h_i ar comput d via simply lin ar transformation. To comput th dg inputs e_{ij} for an dg tw n nod s i and j, w first comput th distanc matrix D, wh r d_{ij} corr sponds to th uclid an distanc tw n PI-Hu s i and j.

Graph Convolution lay r is a r sidual Gat d Graph Conv n t as propos d y Br sson & Laur nt (2017). Th k y asp ct of this archit ctur is th dg gating m chanism which na l s th mod l to l arn importanc for dg s in th TSP or VRP pro l m.

$$h_i^{\ell+1} = \mathrm{ReLU}\left(U^\ell h_i^\ell + \frac{\sum_{j \to i} \eta_{ij}^\ell \odot V^\ell h_j^\ell}{\sum_{j \to i} \eta_{ij}^\ell + \epsilon}\right)$$

η_{ij}^ℓ ar th dg gat s, $\eta_{ij} = \sigma\left(A^\ell h_i^\ell + B^\ell h_j^\ell\right)$. A^ℓ and B^ℓ param t rs l arn d at dg gat s ar th n us d to comput dg f atur v ctor e_{ij}.

ϵ is a small positiv constant to avoid division y z ros, and $ReLU$ is th r ctifi d lin ar unit ($ReLU(z) = max(0, z)$) appli d l m nt-wis to its input.

Th final lay r in th mod l archit ctur is Multi-Lay r p rc ptron classifi r us d to comput th pro a ility of dg m ddings e'_{ij} for ing conn ct d in th final TSP/VRP tour of graph. For xampl , *softmax* op ration can us d with 2-lay r p rc ptron as follows:

$$w_{ij} = \text{softmax}\left(\theta_1 \text{ReLU}\left(\theta_2\, e'_{ij}\right)\right)$$

W also xp rim nt d with anoth r ncod r with Graph att ntion N twork lay r following Transform rs (Vaswani t al., 2017) archit ctur . In this archit ctur , att ntion m chanism is us d as w ight d m ssag passing tw n nod s in th graph. On of th n fits of att ntion m chanisms is that th y allow for d aling with varia l siz d inputs, focusing on th most r l vant parts of th input to mak d cisions. Th w ight of th m ssag valu that a nod r c iv s from a n igh or d p nds on th compati ility of its qu ry with th k y of th n igh our as shown in **Figure 6.6**.

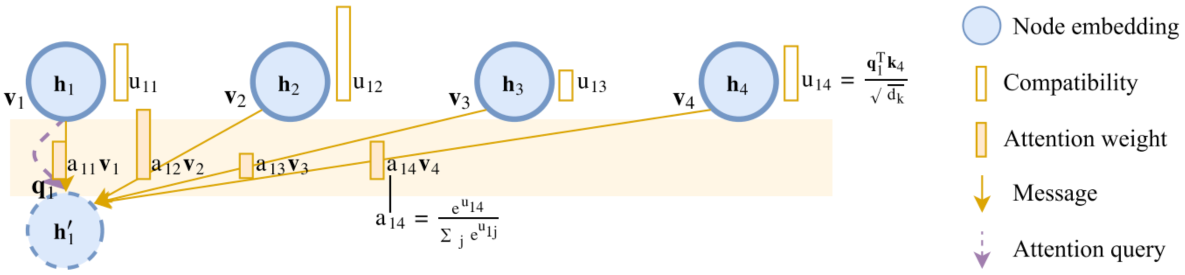


Figure 6.6: Attention mechanism. Image source (Kool et al., 2019)

$$\mathbf{q}_i = W^Q \mathbf{h}_i, \mathbf{k}_i = W^K \mathbf{h}_i, \mathbf{v}_i = W^V \mathbf{h}_i$$

Compati ility of nod i with j is comput d as:

$$u_{ij} = \begin{cases} \dfrac{\mathbf{q}_i^T \mathbf{k}_j}{\sqrt{d_k}} & \text{if } i \text{ adjac nt to } j \\ -\infty & \text{otherwise} \end{cases}$$

From nod s compati iliti s, att ntion w ights ar comput d

$$a_{ij} = \frac{e^{\omega_{ij}}}{\sum_{j'} e^{u_{ij'}}}$$

Finally, th $\mathbf{h}'_i$ v ctor is r c iv d y nod i is com inations of m ssag s v_j.

$$\mathbf{h}'_i = \sum_j a_{ij}\, \mathbf{v}_j$$

In th impl m ntation of att ntion m chanism, w adapt d th archit ctur propos d in (Kool t al., 2019), wh r ach att ntion lay r consists of two su lay rs: a multi-h ad att ntion (MHA) lay r that x cut s m ssag passing tw n th nod s and a nod wis fully conn ct d f d-forward lay r. ach su lay r adds a dropout and a atch normalization (*BatchNormalization* (BN) us d h r). Th MHA lay r us s 8 h ads and th f d-forward su lay r has on hidd n su -lay r with dim nsion 512 and *ReLu* activation.

$$\hat{\mathbf{h}}_i = \mathrm{BN}^{\ell}\left(\mathbf{h}_i^{(\ell-1)} + \mathrm{MHA}_i^{\ell}\left(\mathbf{h}_1^{(\ell-1)}, \dots, \mathbf{h}_n^{(\ell-1)}\right)\right)$$

$$\mathbf{h}_i^{(\ell)} = \mathrm{BN}^{\ell}\left(\hat{\mathbf{h}}_i + \mathrm{FF}^{\ell}(\hat{\mathbf{h}}_i)\right)$$

D

D cod r outputs th n xt nod in th solution as d on m ddings of nod from th ncod r and th outputs g n rat d at tim t s qu ntially. ach su lay r has two su -lay rs of MHA and fully conn ct d f d-forward. Similar to th ncod r, ach su -lay r adopts r sidual conn ction and a lay r *BatchNormalization*. Th k y l m nt in th d cod r is th cont xt m dding v ctor. Th cont xt at tim t consists of th m ddings of th graph, th pr vious nod at t-1 and th first nod . ss ntially, w follow th att ntion d cod r from propos d in (Kool t al., 2019), which starts from a random nod and outputs pro a ility distri ution ov r its n igh ors at ach st p. At tim st p t at nod i, th d cod r uilds a cont xt $\hat{h}_i^C$ for th partial tour $\pi'_{t'}$, g n rat d at tim $t' < t$, y packing tog th r th graph m dding hG and th m ddings of th first and last nod .

$$\hat{h}_i^C = W_C\left[h_G, h_{\pi'_{t-1}}^L, h_{\pi'_1}^L\right]$$

Th cont xt is th n r fin d via a MHA ov r nod m ddings:

$$h_i^C = \mathrm{MHA}\left(Q = \hat{h}_i^C, K = \{h_1^L, \dots, h_n^L\}, V = \{h_1^L, \dots, h_n^L\}\right)$$

In ord r to s arch for solution for TSP or VRP, on approach is to start from first nod and th n w s l ct a nod from its n igh ours as d on th high st pro a ility from d cod r; i. . *greedy search*. If our d cod r is as d on MLP on nod m ddings produc d y th final GNN ncod r lay r L, w can comput unnormaliz d dg logits:

$$\hat{p}_{ij} = W_2\left(\mathrm{ReLU}\left(W_1\left(\left[h_G, h_i^L, h_j^L\right]\right)\right)\right), \text{wh r } h_G = \frac{1}{n}\sum_{i=0} h_i^{L_i}$$

Th logits $\hat{p}_{ij}$ ar conv rt d to pro a iliti s ov r ach dg p_{ij} via a softmax function. Sinc th pro a iliti s ar ind p nd nt of ach oth r, h r w can o tain a valid TSP/VRP tour using gr dy s arch to trav rs th graph starting form a random nod and masking pr viously visit d nod s.

To furth r improv th quality of solution am s arch can us d. A am s arch is a limit d-width r adth-first s arch. For a s qu nc to s qu nc mod l, a am s arch xpands at v ry st p $t = 0,1,2,\dots$ at with width b partial s qu nc s with high st pro a ility to comput th pro a iliti s with l ngth $t + 1$. Similarly, w can sampl b solutions from th d cod d solutions and s l ct th short st tour among th m.

Th final st p adapt d approach is policy l arning. Th r ar two ways to l arn optimal solution policy; on is through sup rvis l arning wh r d cod r output is au[illegible] l ngth $L(\pi)$, wh r $p_\theta(\pi \mid s)$ is th pro a ility distri ution from which w sampl to o tain th tour $\pi|s$.

Our xp rim nts ar limit d to TSP and two variants of VRP, CVRP and SDVRP. For TSP w impl m nt oth Convolution and att ntion as d mod ls (Graph ConvN t and Graph Att ntion N t r sp.) and for th VRP our impl m ntation is limit d to att ntion mod l only. First, data is simulat d for TSP and VRP and o j ctiv functions ar d fin d (s D2.4 for d tails on o j ctiv functions for diff r nt variant of VRP). Th mod ls ar train d for varia l graph siz s with 10, 20, 30 and 100 nod s which ar th conv ntional siz to nchmark TSP or VRP in th lit ratur . For th oth pro l ms, w us sam hyp rparam t rs.

C

W impl m nt d two typ s of configurations:

1. Thr GNN ncod r lay rs follow d y att ntion d cod r h ad with 128 hidd n dim nsions.
2. Four GNN ncod r lay rs follow d y *softmax* dg pr dictor.

W us a constant l arning rat $\eta = 10^{-4}$. Th st configuration was Graph ConvN t ncod r with MAX aggr gation and BatchNorm follow d y att ntion m chanism d cod r. All th mod ls ar train d via sup rvis l arning with ground truth achi v d from st known xact solv r Concord (Appl gat t al., 2006) for th TSP and unsup rvis d l arning for th VRP. Mod ls ar train d using th Adam optimiz r for 10 pochs with a atch siz of 128 and for r inforc m nt l arning, mod ls ar train d for 100 pochs on 128,000 TSP sampl s which ar randomly g n rat d for ach poch (without optimal solutions) with th sam atch siz and l arning rat .

E

Mod l's valuation is p rform d on t st s t, th graph o tain d from d cod r is conv rt d to valid solution via s arch strat gi s d scri d in s ction 3.5. Optimality gap and pr dict d av rag tour l ngth m trics ar us d to valuat mod l p rformanc . Optimality gap is th av rag p rc ntag ratio of th pr dict d tour l ngth r lativ to optimal solution (o tain d from xact h uristics such as Concord , LKH3).

For th TSP, optimal solution is achi v d y xact h uristic solv rs such as Concord (Appl gat t al., 2006, and LKH3 (H lsgaun, 2017). W also compar our r sults with N ar st N igh our which is a non-l arn d as lin algorithm. W also compar r sults with OR Tool solv r. For th VRP, w consid r CVRP and Split D liv ry VRP and compar r sults with r sults o tain d y Nazari t al., (2018) from th ir RL as d solution.

In this s ction w r port on xp rim nt d w conduct d using propos d fram work wh r w l v rag d xact solv rs for optimal solutions as w ll as l arning as d solutions to our TSP/VRP in th proj ct.

For th machin l arning approach s to TSP and VRP is as d on training and valuating mod l p rformanc on pro l m instanc s of fix d siz s. W train thr mod ls training s ts of 500k instanc s with 20, 50 and 100 nod s in ach and valuat th m on t st datas t of 10k instanc s. For th training loop, cross- ntropy loss with stochastic gradi nt d sc nt was us d and training r sults in a an adjac ncy matrix corr sponding to a TSP tour.

During th valuation, adjac ncy matrix o tain d from Graph ConvN t is transform d into a valid solution via s arch strat gi s d scri d in pr vious s ction. W us pr dict d tour l ngth and optimality gap (optimal solution is o tain d from Concord solv r) following th study (Kool t al., 2019). Th av rag pr dict d tour l ngth ov r t st datas t is comput d as $\frac{1}{n}\sum_{i=1}^{n} \hat{l_i}$ and optimality gap is th ratio of pr dict d tour l ngth r lativ to th optimal solution ov r t st s t, comput d as: $\frac{1}{n}\sum_{i=1}^{n}(\frac{\hat{l_i}}{l_i} - 1)$

Table 6.4 Performance of Graph ConvNet against exact and heuristic solutions

Concord	3.84	0.0%	1m	5.7	0.0%	2m	7.76	0.0%	3m
LKH3	3.84	0.0%	18s	5.7	0.0%	5m	7.76	0.0%	21m
Nearest Neighbor	4.5	17.23%	0s	7.0	22.94%	0s	9.68	24.73%	0s

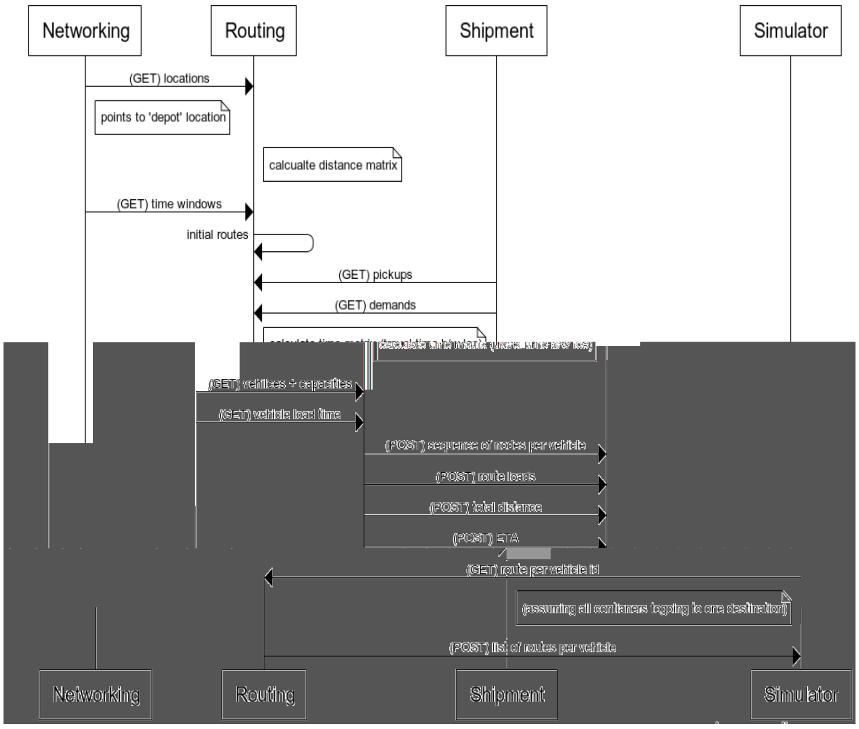

Networking
Routing
Shipment
Simulator
(GET) locations
points to 'depot' location
calcualte distance matrix
(GET) time windows
initial routes
(GET) pickups
(GET) demands
(GET) vehicles + capacities
(GET) vehicle load time
(POST) sequence of nodes per vehicle
(POST) route loads
(POST) total distance
(POST) ETA
(GET) route per vehicle id
(assuming all containers going to one destination)
(POST) list of routes per vehicle
Networking
Routing
Shipment
Simulator

Figure 6.7: Integration of routing service with others in ICONET

7 DISCUSSION AND CONCLUSIONS

In this r port w analys d th transport proc ss s of shipping, ncapsulation, n tworking and routing und r th prism of PI. It is argu d that th uniqu n ss of th PI, aris s du to th mphasis on c rtain asp cts of transportation such as multipl parti s, mor rout and war hous /hu acc ssi ility and multi-l g transport chains. ss ntially, this l ads to mor opportuniti s for id ntifying ffici nci s through mor nvironm ntally fri ndly rout s, undling, high r pot ntial to r duc mpty runs tc.

PI may how v r incr as som of th risks of transport, du for xampl to an incr as in th num r of touching points' for cargo. Th n d for proc ss coordination tw n unknown to ach oth r parti s, also plac s mor mphasis on standardisation of th xchang d information. Th GPICS data structur was consid r d as a starting point for d v loping a compr h nsiv data structur , that na l s th PI to mak inform d d cisions on th utilisation of infrastructur , ass ts and d c ntralis d capa ility.

Th r port pr s nts th Physical Int rn t (PI) four cor s rvic s, nam ly th Shipping, ncapsulation, Routing and N tworking. Th s rvic s hav n d sign d to align with th OLI/ NOLI (and ICON T) lay rs na ling a standardis d approach to th PI impl m ntation. Th ontology of PI Links, Nod s and S rvic s is xt nd d as ach s rvic is xamin d into furth r d tail. Th s rvic s ar d sign d to account for various usin ss typ s wh r various us cas s aris . Th s qu nc of communications of th PI S rvic s d sign has n consid r d for ach us cas , aiming to na l th d v lopm nt of modular and ro ust s rvic s. Th various applications cont xts of th PI hav also n taking into account, drawing on th adaptations of th four cor s rvic s to th ICON T Living La r quir m nts. In th r port w addr ss d transport proc ss s in th natural s qu nc in which th y occur:

- Shipping: It has an ov rarching manag r rol and can divid d into: d sign; initialization; arrival at PI nod ; and r al tim updat modul s. Th function of th first two modul s is associat d with th r qu st of shipm nt through th and th d v lopm nt of th PI Ord r. Th Arrival at PI nod modul handl s th s qu ntial hops of PI contain rs in th ir rout to th ir d stination, whil th r al tim updat s modul , communications with th IoT platform and coll cts data to track th p rformanc of th PI shipm nt against its contractual o ligations.
- ncapsulation. It inv stigat s th in packing algorithm as w ll as algorithms for ov rcoming its computational compl xity. Th ncapsulation s rvic addr ss s th ncapsulation of cargo into PI contain rs of various siz s and into PI Mov rs/M ans. It off rs a g n ric tool for improving op rational ffici ncy and d cision making at PI Hu s. Variations of th g n ric mod l ar d scri d that can also utilis d for ffici nt Comm rc ncapsulation.
- N tworking: Th n tworking s rvic primary function is n twork discov ry, in ord r to provid a standardis d and compl t r pr s ntation of th PI for furth r d cision making. Using th GPICS as a guid lin , an nhanc d data structur is propos d r aking down th PI n twork information into static and dynamic data for PI Links, PI Hu s and PI Mov rs. Furth rmor , consid ring th ICON T Living La s, s v ral n twork r pr s ntation approach s ar consid r d focusing at varying n twork aggr gations. A guid lin for n tworking s rvic impl m ntation into diff r nt cont xts is also provid d.
- Routing: Th routing s rvic inv stigat s th computational compl xity and h uristics for improving th solution tim for g n ric and sp cialis d PI routing pro l ms. Th p rformanc

of m thods utilising an int gration of optimisation and machin l arning m ans ar discuss d in d tail, for proposing an PI.

Th multipl int rconn ctions of th ICON T S rvic s, na l accommodating into th Physical Int rn t various typ s of usin ss s ranging from Manufactur rs, to Logistics op rators, and Comm rc . A compl x communications syst m manag d y ICON T Shipping S rvic was shown to handl various typ s of Us Cas s, including:

- th r -routing of shipm nt wh n n twork status has chang d,
- th r -ass ssm nt of PI Ord r priority in cas of d lays, and
- th continuous ass ssm nt of shipm nt m trics against PI Ord r t rms, which in cas of violation can l ad to r - valuation of PI Ord r through Shipp r validation.

Qu uing th ory was discuss d for accurat ly id ntifying ffici nt and in ffici nt routing options, and an nhanc PI Link r pr s ntation was propos d for simplifying and aggr gating th PI n tworks op rational f atur s.

Additional analytic compon nts w r consid r d for accommodating industry sp cific pro l ms, such as th lack of fulfilm nt origin in th cas of Comm rc . Additionally, nhanc d PI Nod data structur was propos d to accommodat Comm rc r l vant information. All th a ov proc ss s ar impact d y th inh r nt charact ristics of transport and logistics which ar ss ntially distri ut d (in spac and in tim), multi-party, multi-modal and stochastic.

Information t chnology can improv many ffici ncy param t rs; how v r, it cannot liminat unc rtainti s and risks that ar naturally occurring in transport. PI provid s mor options to mitigat such risks (.g. y switching to diff r nt mod s or rout s) thus making transportation pot ntially mor r sili nt. Th propos d information/data structur na l s PI S rvic s to mak tt r and smart r op rational d cision and d liv r a mor ffici nt PI.

S rvic s for tracking and tracing cargo through its PI journ y may com mor important, as in PI cargo may trav l through unknown (to th plann r) n tworks. In this r port, w illustrat d th pot ntial of a n w class of rout plann rs that can plan rout s through PI following paths across conn ct d π-hu s. Th s plann rs go yond curr nt multimodal transportation plann rs as th switching of cargo is not only tw n mod s ut also tw n rout s crossing diff r nt transport n tworks. This allows to xploit syn rgi s for cargo undling and mor ffici nt and nvironm ntally fri ndly routing.

An nd-to- nd fram work for solving larg scal routing pro l ms was introduc d. Th input to th fram work is PI n twork as prop rty graph and th pro l m instanc . Th Graph n ural n twork-as d ncod r-d cod r archit ctur along with s arch compon nt d t rmin a s t of solutions which th n is optimiz d y th policy l arning compon nt through sup rvis d l arning or r inforc m nt l arning. Th sup rvis d l arning is as d on ground truth a solution achi v d y st known h uristic for a giv n TSP or VRP pro l m instanc . In our xp rim nts w l v rag d LKH3 and Concord solv r for TSP and OR-Tool for th VRP. W also xp rim nt d with R INFORC algorithm for l arning th policy gradi nt as as lin for oth TSP and VRP. Th mod ls train d with sup rvis d l arning ar d p nd nt on th h uristic s arch wh r as r inforc m nt l arning approach s scal tt r with mor computation as th y do not r ly on la ll d data. Although fram work com in s th str ngth h uristic algorithms with l arning ov r larg data using Graph n ural n tworks ut it's scop is limit d to simpl TSP and two variants of th VRP: Capacitat d V hicl Routing Pro l m (CVRP) and V hicl Routing pro l m with Tim window (VRPTW).

All S rvic s pr s nt d in this r port hav n int grat d with th PoC Platform. Th communication tw n th PoC has n impl m nt d y using ith r dir ct (S rvic X to S rvic Y) or indir ct (S rvic X – Simulation – S rvic Y) Application Programming Int rfac s (API). Th impl m ntation of th PoC is xp ct d to off r furth r validat th ffici ncy PI S rvic s d liv r and can pot ntially ncourag furth r inv stigation.

A arri r in th d v lopm nt of th s rvic s has n th lack of visi ility to th sourc s of stochasticity in th logistics supply chain. Th gradual improv m nt of th r pr s ntation of th ICON T Physical lay r, that captur s th location and status of s rvic s through s nsors and data transf rs is xp ct d to off r nhanc d visi ility of supply chain unc rtainty, and contri ut in ov rcoming this limitation. As th PI matur s, th Cor PI S rvic s, will n d to handl mor functionality and compl xity to ff ctiv ly manag T&L supply chain. Anoth r asp ct wh r furth r d v lopm nt is anticipat d is th communication of PI S rvic s with xisting s nsing and l gacy manag m nt syst ms. As th PI will grow furth r xt nsions and sp cial cas modul s will r quir to com part of th cor ICON T s rvic s to allow for incr as d availa ility and op nn ss of th n twork, without compromising xisting usin ss op rations. This will also ncourag th asi r xpansion of th n twork with, mor r lia l data and incr as d trust among Supply Chain actors.

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