LUNDS TEKNISKA HÖGSKOLA

Problemet med marin påväxt och dess lösningar

En litteraturstudie

Niklas Hansson och Erik Wilson

Handledare: Professor Lars Montelius

LUNDS UNIVERSITET
Lunds Tekniska Högskola

Abstract

With a fuel consumption of up to *150 tons* a day for a containership, fuel cost is the main expense for shippers. To decrease expenses, drag reduction is the most important topic to address. The biggest factor that influence the hydrodynamics of a vessel is marine fouling. A heavily fouled ship can consume an additional *40 %* of fuel, or more (1). The process of marine fouling is an extremely diverse and complex issue, involving more than 4000 marine fouling species (2) that interact with the vessel surface. On top of that, the microbiological environment is dramatically different between different regions of the world and the oceans.

Marine antifouling suppliers push development in order to meet the demands from shippers all around the world requiring constantly higher and higher performance. The development is directed towards achieving better performance but it is also controlled by regulations. To be able to meet future demands, new laws and regulations has to be monitored, understood and considered. Biological systems are being studied for inspiration and more novel and complex solutions are constantly emerging. The solutions have shifted from only tackling hard macrofouling to also focus on preventing the biofilm from forming.

Stricter regulations mean that the environmental considerations become more and more important for the shipping industry. The positive effects of antifouling solutions on lowered exhaust gas emission have to be balanced in relation to its environmental load arising from biocidal release. Especially since the shipping fleet is behind some of the worst exhaust emissions in the world.

In this work, today's antifouling solutions have been researched, compared and stripped, to more easily see the lowest common denominators in order to predict a future solution. A future solution must have higher performance, tackle the biofilm from forming, be easy to apply, free from biocides and lasts the entire life-time of the vessel.

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Sammanfattning

Ett containerfartyg förbrukar upp till 150 ton bränsle per dag vilket gör bränslekostnaden till den största utgiften för redare. Ett sätt att minska kostnaderna är att minska fartygens friktion. Den yttre faktorn som har störst påverkan på ett fartygs hydrodynamik är marin påväxt. Ett fartyg med kraftig marin påväxt kan förbruka ytterligare *40 %* bränsle eller mer (1). Marin påväxt är en process som involverar mer än 4000 arter av marina organismer (2). Det är en mångsidig och komplex mikrobiologisk process som har olika förutsättningar beroende på havsmiljö.

Runt om i världen utvecklas nya och mer komplexa metoder och skydd mot marin påväxt. Redarna kräver allt högre prestanda och ställer därför allt högre krav på produkter som kan minska effekten av marin påväxt. Utvecklingen drivs framåt av högre krav men styrs och bromsas av olika former av regleringar. Det är viktigt att industrin och forskare skaffar sig inblick i hur utvecklingen av lagar kommer att leda till förändrade förutsättningar. EU förutspås till exempel göra det ännu svårare för företag att introducera nya biocider (gifter mot marin påväxt) på marknaden. Idag studeras därför biologiska system för inspiration till nya och mer hållbara lösningar. Utvecklingen har skiftat fokus från att tidigare endast handla om hanteringen av den kraftigaste marina påväxten, till att nu också försöka förhindra bildandet av biofilmer, den enklaste formen av marin påväxt.

Sjöfartsnäringen står för några av de värsta avgasföroreningarna i världen och biocidutsläpp har negativa konsekvenser för haven. Skärpta krav och regelverk innebär att produkters miljöeffekter får allt större betydelse. Samtidigt måste lösningar för att förhindra marin påväxt ställas mot miljöeffekter från både biocidutsläpp och avgasutsläpp.

Inom detta arbete har vi genom litteraturstudier och intervjuer kartlagt dagens metoder för att förhindra marin påväxt. Genom att undersöka dessa metoder har de kunnat jämföras för att lättare se vad alla har eller inte har gemensamt, i syfte att bättre kunna förutsäga vad en framtida lösning kräver. En framtida lösning bör ha högre prestanda, förhindrar att biofilmer formas, är lätt att applicera, vara fri från biocider och vara hela fartygets livslängd.

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Inledning

Marin påväxt kallas den ofrivilliga påväxt på hårda substrat som sker i marina miljöer och som leder till ett ökat vattenmotstånd för fartyg och båtar. Sjöfartsnäringen transporterar *80 %* (3) av alla världens varor. Den huvudsakliga utgiften för ett fartyg är bränslekostnaden. En kraftig påväxt kan öka bränsleförbrukningen med mer än *40 %* (1). Att förhindra marin påväxt är därför av största intresse för rederier och båtägare i deras försök att minska kostnaderna.

Processen för marin påväxt är extremt mångsidig och komplex. Den omfattar mer än 4000 olika arter av marina organismer och varierar mellan regioner och världshav (2). För att förhindra denna påväxt finns det idag en mängd olika lösningar ute på marknaden. Dessa verkar främst genom att innehålla biocider. Användningen av biocider är starkt kontrollerad till följd av dess negativa effekter på hav och sjöar. Det finns biocidfria alternativ och mycket forskning sker kring så kallade *fouling release* färger (färger med så hal yta att organismer inte kan hålla sig kvar medan fartyget kör). Marknaden domineras idag av olika typer av skyddsfärger som framför allt innehåller koppar som biocid för att skydda mot marin påväxt.

Nanoteknik har identifierats som ett nyckelområde för att ta fram effektivare och miljövänligare metoder mot marin påväxt. Även bioinspiration och biomimetik har fått allt större uppmärksamhet de senaste åren.

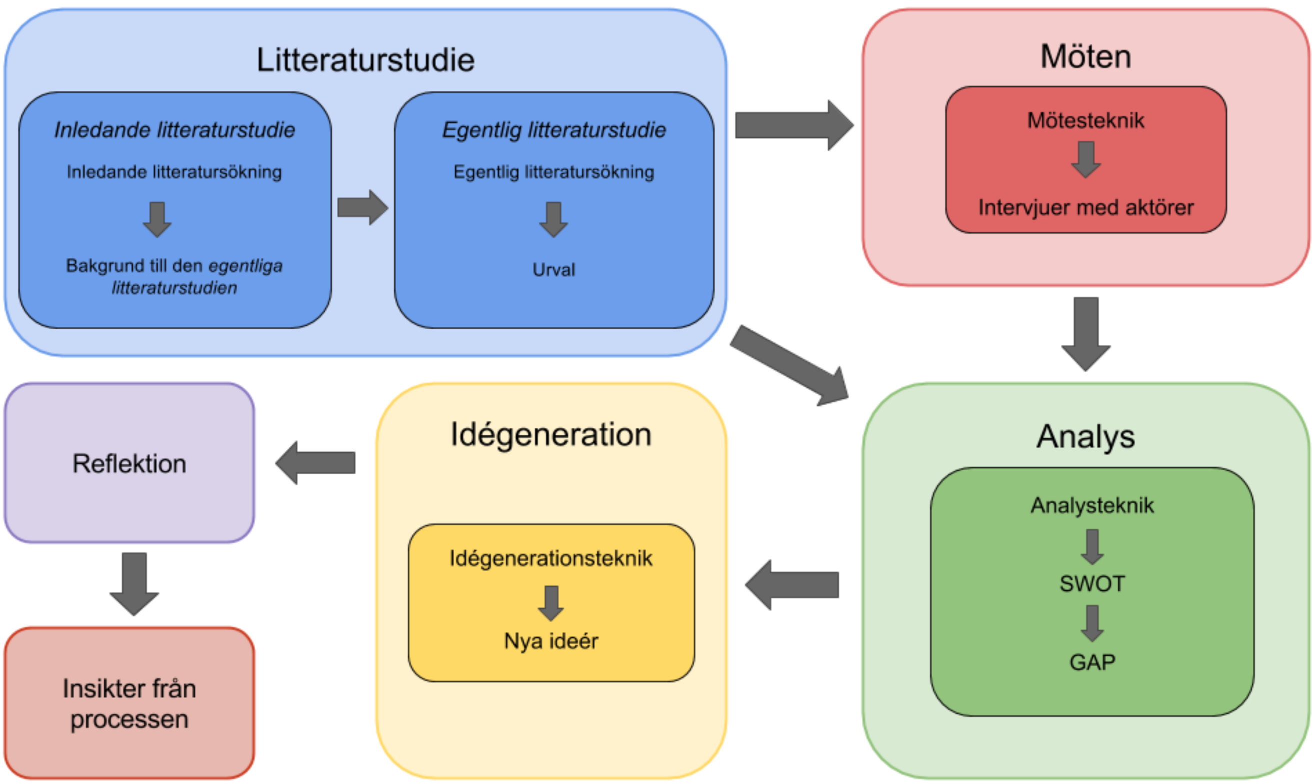
Rapporten har delats in i två delar. I den första delen, **Processen**, redovisas alla val av metoder, underbyggda med teori och utvärderingar samt hur arbetet har utförts. Den andra delen, **Scientific Report,** är skriven på engelska, detta för att förenkla skrivprocessen då korrekt terminolog inte finns på svenska. Den innehåller litteraturstudien, analyser av dagens lösningar och resultatet av möten med branschexperter samt förslag till framtida lösningar.

Problemformulering

I denna uppsats kartläggs hur marin påväxt förebyggs och förhindras idag, för att finna nya sätt att minimera marin påväxt. För att uppnå detta studerades hur naturen löser problemet med marin påväxt, vad rederierna har för önskemål på en framtida produkt samt vilka metoder som idag används för att förhindra marin påväxt. Syftet är att finna nya lösningar som har en mindre negativ effekt på miljön än de nuvarande. Dessa ger både direkt negativa effekter till följd av biocidutsläpp och indirekt negativa effekter till följd av de ökade avgasutsläpp som den marina påväxten bidrar till. För att kartlägga problemet med marin påväxt användes artiklar, böcker samt intervjuer med aktörer som jobbar med marin påväxt. Dagens lösningar till marin påväxt analyserades med hjälp av SWOT- och GAP-analys.

Processen

Arbetsprocessen har delats in i litteraturstudier, möten, strategisk analys, idégeneration och insikter från processen. Dessa delar har varsin tillhörande rubrik som syftar till att beskriva nämnd process. Figur 1 nedan syftar till att illustrera arbetsprocessens flöde.



Figur 1 En illustration över arbetsprocessens olika steg från litteraturstudien till insikter från processen.

Litteraturstudie

Litteraturstudien hade som mål:

- *Uppnå en kunskapsnivå som gör det möjligt att förstå de metoder som industri och forskare arbetar med*
- *Undersöka hur naturen förhindrar marin påväxt*
- *Undersöka de huvudsakliga metoder som används idag*
- *Skaffa en djupare förståelse för de bakterier, växter och djur som orsakar marin påväxt med fokus på dess infästande mekanismer*.

Litteraturstudien kan delas in i två delar, den *inledande*- och den *egentliga litteraturstudien* (4). Gemensamt för båda är att en kontinuerlig dokumentation av metod, tillvägagångssätt och resultat görs. Dokumentation är viktig för att få en tydlig struktur avseende insamlad data.

För att få en systematisk sökning men samtidigt experimentera med informationssökningen utfördes såväl *systematiska*- som *osystematiska sökningar* under både den *inledande litteraturstudien* och den *egentliga litteraturstudien* (4). *Systematisk sökning* innebär att varje sökning ska vara väl planerad och strukturerad samt att tillvägagångssättet dokumenteras och den övergripande planen för sökprocessen följs. Den *osystematiska sökprocessen* är friare och kräver mindre kunskap. Målet med den *osystematiska sökprocessen* är att komplettera den *systematiska informationssökningen* med inspiration och idéer. Den o*systematiska sökprocessen* var dominerande i den *inledande litteratursökningen* samt under *idégeneration*.

Inledande litteraturstudie

Målet med den *inledande litteraturstudien* var att skapa en grund för sökarbete och ge oss en översikt över problemet med marin påväxt. Under den inledande fasen blev problemets vidd uppenbar. Nyckelbegrepp, frågeställningar och intressanta källor sammanfattades och dokumenterades inför den *egentliga litteraturstudien*.

Lunds universitetsbibliotek tillhandahåller möjligheten att få hjälp av en bibliotekarie kring litteraturstudier och databaser. Eftersom forskning inom marin påväxt inte bedrivs vid Lunds universitet kontaktades bibliotek från lärosäten där forskning kring marin påväxt bedrivs såsom Chalmers, Stockholms universitet och Linköpings universitet. De mest lämpade databaserna valdes ut och utgjorde grunden för den *egentliga litteraturstudien*.

Den *inledande litteraturstudien* avslutades genom att göra en plan för den *egentliga litteraturstudien.* Målet med detta var att få en effektivare sökprocess. I denna arbetsplan beaktades följande:

- Sökproblem: Definiera vilken typ av information som söks med utgångspunkt från problemformuleringen.
- Avgränsning.
- Sökord och synonymer: Nyckelbegrepp som ska användas vid sökningen. Informationsbehov: Utifrån vilket informationsbehov bestäms sedan typen av informationskällor.
- Tänkbara informationskällor: Vilka typer av källor finns?

Egentliga litteraturstudie

Under den *egentliga litteraturstudien* inhämtades och bearbetades den information som arbetet kom att bygga på. De typer av litteratur som användes var böcker, e-böcker, vetenskapliga artiklar och hemsidor. De mål som sattes för den *egentliga litteraturstudien* var utöver målen för litteraturstudien även att identifiera litteratur som är central inom marin påväxt samt identifiera framstående personer inom fältet för marin påväxt.

Under den *inledande litteraturstudien* identifierats relevanta databaser och följande valdes ut:

- Engineering Village
- BIOSIS
- LibHub
- Web of Science
- Web of Science Core Collections
- Scopus
- Georef
- SciFinder

Varje sökning dokumenterades med databas, sökord, träffar, kommentarer, datum och betyg på sökningen. Arbetet avgränsades till tekniker för att hämma marin påväxt på båtskrov. Urvalet av källor gjordes baserat på antalet citeringar. Undantag från detta gjordes för artiklar vi tyckte visade speciellt lovande och spännande metoder för bekämpning av marin påväxt. Artiklarna värderades också högre om framstående personer inom forskningsområdet marin påväxt medverkat. De litteraturkällor som valdes sparades och följande dokumenterades:

- vilken databas den påträffats i
- med vilka sökord den hittades
- vilket datum sökningen utfördes
- en kort motivering till varför artikeln valdes.

Med dessa enkla steg av dokumentation var målet att sökprocessen ska kunna återskapas med samma resultat som den ursprungligen gjordes. Då arbetet fortskred fördjupades kunskaperna successivt liksom kännedomen om korrekta nyckelbegrepp inom området. Detta ledde naturligt till att sökningarna blev mer precisa allt eftersom. Samtidigt motsvarade också resultatet av sökningarna förväntningarna i högre grad. Under arbetets gång övergick litteratursökningen mer och mer till att baseras på välciterade verk inom forskningsområdet. Genom kontakt med företag och forskare gavs också rekommendationer om artiklar som de ansåg vara viktiga inom området. Under slutet av arbetet upphörde dokumentationen av sökprocessen, det blev för tidskrävande och hämmade sökprocessen.

Möten

Det anses ofta enligt författarna att akademiens akilleshäl ofta är att dess forskning är skild från verkligheten, det vill säga att de finner svar på frågor och problem som inte än existerar. Lösningen på detta blev att komma ut och prata med företag och intressenter inom marin påväxt. Syftet med dessa möten var att få en bättre bild av problemet. Totalt kontaktades 28 företag. Av dessa etablerades kontakt med 10 stycken utav dem.

Nedan följer de delmål som sattes inför möten med företag och intressenter. Det är dessa mål som har påverkat urvalet av företag samt mötesformen.

– *Förbereda samtal inför möten med industrin.*

Förberedelser var att läsa på om företaget, deras produkter och tekniker samt att ta reda på mer om de företagsrepresentanter som skulle delta i mötet.

– *Studera olika mötestekniker och planera möten efter den mötesstruktur som gynnar närvarande mötesdeltagare.*

Hur ser kommunikationen ut mellan företag? Vilken kunskap är de villiga att dela med sig och vad håller de hemligt?

– *Studera olika presentationstekniker.*

Att göra ett seriöst och gott första intryck är av största vikt för framtida samarbeten med olika företag. Därför gäller det att göra det så bra som möjligt genom en tilltalande presentation.

– *Få en inblick i industrin och akademins arbetsprocess.*

Finns det någon skillnad i hur industrin arbetar med sin forskning jämfört med akademin? Ett svar ger möjlighet att anpassa vår forskning därefter.

– *Få en djupare insikt i just industrins och akademins forskningsområden.*

För att inte uppfinna hjulet på nytt är det extra viktigt att känna till vilken forskning som bedrivs idag och vilken forskning som har bedrivits.

– *Få minst en person som erbjuder sig att hjälpa till i idégenerationsfasen.*

Att ha tillgång till en person med expertis inom området kring marin påväxt för att bolla idéer med samt ha som medhjälpare under idégenerationen av arbetet skulle varit till stor nytta.

Att etablera företagskontakter var mer krävande än väntat till följd av sommarens semestrar. Även att nå fram till ämneskunniga inom de större företagen tog mer tid än väntat. Detta ledde till att många kontakter som etablerades blev aktuella först under slutet av arbetet.

Inom forskningsområdet marin påväxt är kulmen *International Congress of Marine Corrosion and Fouling (ICMCF)* som hålls vartannat år. Kongressens hemsida och föredragsagenda gjorde att tidigare okända aktörer inom marin påväxt kunde identifierats och nya kontakter etableras. Handledare Lars Montelius kontaktnät gav många direktkontakter. Detta gjorde att omvägen via företags HR-personal eller dylikt undveks.

Under arbetets gång har företag och personer i Sverige, Danmark, Holland, Belgien, England, Singapore, Australien och USA kontaktats. Sammanfattningsvis gick det bra. Vi blev alltid väl bemötta och hade ett bra informationsutbyte. Det blev endast två platsbesök men desto fler telefonmöten och långa mejlkonversationer. Nedan följer en lista över de företag och branschexperter som har kontaktats.

Kontaktade företag och aktörer

Stora färgföretag

International Paint

Tillverkar industribeläggningar för nybyggnationer och reparationer av skepp. Har verksamhet i 54 länder och över 5400 anställda vilket gör dem till en av världens största leverantörer av marina beläggningar. International Paint ägs av Akzo Nobel och har sitt huvudkontor i Amsterdam.

PPG

Global leverantör av färger, beläggningar, optiska produkter, specialmaterial, glas och glasfiber. Har över 40 000 anställda världen över och är en av världens största leverantörer av skyddsbeläggningar. Har sitt huvudkontor i USA.

Jotun

Företagskoncern med 69 företag och 36 produktionsanläggningar världen över inom färg- och ytbeläggningar. Har sitt säte i Norge med över 8000 anställda.

Hempel

Färgföretag som jobbar med marina, industri-, container-, yacht- och dekorativa beläggningar. Har sitt huvudkontor i Köpenhamn med 5000 anställda världen över.

Chugoku Marine Paints

Producerar och säljer marin- och industrifärger. Baserat i Japan med över 17 000 anställda.

Mindre färgföretag

Sigma Coatings

Ägs av PPG, se PPG.

Nippon Paint

Färgföretag som producerar 17 miljarder liter färg årligen. Har sitt huvudkontor i Japan och är representerade i 15 länder.

Korean Chemical Company (KCC)

Har sitt huvudkontor i Sydkorea och har 4800 anställda. Har en bred produktportfölj med allt från byggmaterial till mer avancerade material. De jobbar även med marina färger.

Transocean Coatings

Tillverkar och säljer färg mot marin påväxt och antikorrosionsbeläggningar till skepp och marina konstruktioner. Har sitt huvudkontor i Rotterdam, Holland.

Biocidföretag

I-tech

Är ett Göteborgsbaserat företag som grundades år 2000 av forskare från Göteborgs universitet och Chalmers. Har utvecklat en biocid som bekämpar infästning av havstulpaner.

aXichem

Beskriver sig själva som ett företag som utvecklar, patenterar och tillhandahåller bioinspirerade industrikemikalier. Har utvecklat en produkt vid namn fenylcapsaicin som de tror kan bli en framtida biocid.

Varv

Oresund Heavy Industries

Ett av Europas största varv, erbjuder tjänster inom reparation, underhåll och ombyggnationer av skepp. Varvet är beläget i Landskrona, 20 minuter norr om Lund.

Rederier

Wallenius Lines

Ursprungligen ett svenskt rederi, nu med huvudkontor i både Sverige och Singapore. Har 160 fartyg med 1,100 besättningsmän och trafikerar 40 rutter världen över.

Akademin

Luigi Petrone, PhD, Chemistry

Har forskat och publicerat artiklar med koppling till marin påväxt.

Malmö högskola, Research Center of Biointerfaces

Malmö högskolas center för forskning kring biofilmer. Har idag främst forskning kring biofilmer i medicinska applikationer men centrat bedrev ursprungligen forskning kring marin påväxt.

SP

Är Sveriges tekniska forskningsinstitut och ägs av svenska helägda eller delvis statligt ägda bolag. Jobbar med forskning och utveckling inom en rad olika områden som också involverar grundforskning.

TNO

Forskningsinstitut i Nederländerna som är icke vinstbedrivande och riktar sig mot tillämpad forskning. Motsvarar svenska SP.

Wyss Institute

Institut för biologiskt inspirerad forskning vid Harvard. Inspirerade av naturen forskar de inom hälsa, energi, arkitektur, robotar och framställning.

Företag med nya lösningar

Philips
Ett av världens största elektronikföretag med en stor forskning inom lysdioder och dess tillämpningar. De håller bland annat på att utveckla en metod mot marin påväxt som bygger på UV-ljus.

Sharklet
Bioteknikföretag som har utvecklat en ytbeläggning med en mikrostruktur som drastiskt minskar bakterietillväxt. Tekniken är inspirerad av strukturen hos skinnet på hajar.

Nanocyl
Tillverkare av kolnanorör för industri och specialtillämpningar. Företaget deltog i ett forskningsprojekt kring marin påväxt kallat AMBION där de bidrog med att utvecklade en tillsats till *fouling release* beläggningar.

Övriga

Kapten Peter Listrup
Har mångårig kaptenserfarenhet från olika regioner i världen. Arbetar idag som direktör för fartygssimulatorn Smartship Australia, i Brisbane, Australien.

Försvarets Materielverk (FMV)
Är en civil myndighet som tillhandahåller, utformar och förser försvaret med material och tjänster.

European Defence Agency (EDA)
Samarbetsorganisation för europeiska försvarsfrågor. Har som mål att förstärka Europas och medlemsländernas försvar genom gränsöverskridande samarbete. Inom EDA bedrivs forskning kring marin påväxt för militära fartyg.

Saab Group och Kockums
SAAB Group har genom sitt uppköp av Kockums stora kunskaper om skepps- och ubåtskonstruktion.

Kemikalieinspektionen
Tillsynsmyndighet för kemikaliekontroll i Sverige. Har till syfte att skydda hälsa och miljön från farliga ämnen. Godkänner kemikalier för användning i Sverige.

Paintbox
Underentreprenör till Kockums. Utför ytbehandling på både civila och militära farkoster.

Premator
Jobbar globalt med korrosionskontroll på främst marina konstruktioner.

Etablerade kontakter

Besök

Totalt besöktes endast två företag. Detta till följd av svårigheter med företagskontakt och att endast ett fåtal av de företag som jobbar med marin påväxt ligger i vår närregion (region Skåne).

i-tech

Genom möte med i-tech skapades förståelse för branschen. Mycket diskuterades om svårigheterna med att införa en ny biocid på marknaden och hur färgbranschen fungerar.

Research Center for Biointerfaces

Berättade hur forskning om biofilmer bedrivs på Malmö högskola och möjligheterna för ett framtida samarbete.

Telefonmöten

Med företagen nedan hölls telefonintervjuer. Frågor skickades på förhand via mejl som besvarades och diskuterades under samtalen.

International Paints, IP

Gav en insikt i hur färgföretagen arbetar med särskilt fokus på *fouling release* färger.

Kapten Peter Listrup

Samtalet innehöll bland annat en diskussion om kaptenens roll vid val av skydd mot marin påväxt. Frågor som också besvarades under samtalet var de om hur stor kunskap och medvetenhet redare har om problemet med marin påväxt.

Wallenius Lines

Med Wallenius diskuterades framtiden för marin påväxt och dess lösningar, hur stort problemet faktiskt är, vilka lösningar de vill se på marknaden och vad de är beredda att göra för att se dem realiseras.

Nanocyl

Samtalet kom att handla om hur mekanismen fungerar i deras produkt *Biocyl*. *Biocyl* används som en tillsats i *fouling release* beläggningar.

Mejlkorrespondens

Följande aktörer besvarade frågor över mejl. Samtliga var tillmötesgående och omfånget på frågorna gjorde att varken besök eller telefonmöte var nödvändigt.

Luigi Petroni

Luigi Petroni (Dr) är anställd vid Nanyang Technological University i Singapore där han forskar på marin påväxt och bland annat har jobbat med havstulpaners beteende. Han har varit till stor hjälp och funnits med som bollplank under arbetets gång.

Philips Research Laboratories

Dessa kontaktades för att svara på frågor om en ny teknik mot marin påväxt som presenterades på årets *ICMCF*, en teknik som involverar emission av UV-ljus från fartygsskrov.

Sharklet

Företaget kontaktades för att få ökad kunskap om framtida utveckling av deras bioinspirerade produkt Sharklet.

Kemikalieinspektionen

Regelverk för biocider och deras utveckling diskuterades.

Övriga

Företagen som inte nämns under *besök*, *telefonmöten* eller *mejlkorrespondens* har antingen uteblivit med svar eller har inte kunnat erbjuda något informationsutbyte.

Mötestekniker

Under arbetets gång genomfördes möten och telefonkonferenser med olika aktörer. För att förvalta tiden på bästa sätt och ge ett gott intryck studerades mötesteknik. Följande råd ger en möjlighet att planera och utföra ett så bra möte som möjligt. Dessa går att implementera på både vanliga möten såväl som på telefonmöten. För att genomföra ett lyckat möte kan planeringsprocessen delas in i tre steg: före, under och efter mötet.

Huvudregler

För ett väl fungerande möte gäller att:

- målet med mötet uppnås
- mötet upptar minimalt med tid
- deltagarna är närvarande och deltar aktivt
- deltagarna upplever att mötet tillfört något.

Före mötet

- Definiera era mål för mötet och forma mötet kring dessa.
- Planera inte för detaljerat. Var beredd på att vara flexibel. Ett lyckat möte är ett som mötesdeltagarna känner att de kan påverka.
- Använd tiden effektivt. Prioritera vilka mål som är viktigast. Planera en dagordning i ett strömlinjeformat format så att punkter som har med varandra att göra kommer i en naturlig följd och onödiga utsvävningar undviks.
- Skicka om möjligt de viktigaste frågorna till företaget ett par dagar före mötet och uttryck vad syftet med mötet är. Då har alla mötesdeltagare samma utgångsläge.

Under mötet

Inledningsvis:

- Tacka mötesdeltagarna för att de tar sig tid att närvara.
- Gå igenom mötesagendan tillsammans och avsätt tid till vardera punkt, så att ingen omedvetet drar ut på tiden.
- Klargör er roll i mötet.

Under mötets gång:

- Ha kontinuerliga ”nöjes-avcheckare” där ni uppmärksammar hur deltagarna mår. Försök titta upp och notera kroppshållning. Stanna upp i diskussionen om deltagarna ser trötta och hängiga ut och låt alla deltagarna yttra sig. Det kan exempelvis finnas behov för en paus.

I slutet:

- När ni känner att ni har nått en överenskommelse eller att era mål med mötet är uppfyllda summeras mötets innehåll.
- Producera en “Action-list” som klargör vad deltagarna förväntas utföra, vem som ska göra vad, vilken prioritet det har och tills när det ska vara utfört.

Efter mötet

- Tacka samtliga deltagare för mötet.
- Skicka en kopia på den “action-list” ni gemensamt tog fram samt en mötessammanfattning över mötet om behovet finns (5, 6).

Strategisk analys

De lösningar mot marin påväxt som idag tillhandahålls analyserades och relaterades till de efterfrågade kriterierna för en framtida lösning. För att kunna analysera dagens lösningar och jämföra dessa, gjordes först en SWOT-analys (*Strengths*, *Weaknesses*, *Opportunities* och *Threats*) och därefter en GAP-analys. Dessa beskrivs i korta drag nedan. Syftet med GAP-analysen var att belysa skillnaderna mellan dagens lösningar och den ideala lösningen på problemet med marin påväxt. Den strategiska analysen låg till grund för *idégenerationsfasen* då den gav kunskap om vilka önskemål som finns på en framtida lösning samt belyste de brister som finns hos dagens lösningar. De delmål som sattes för den strategiska analysen var:

- *Att studera och komma fram till den mest lämpliga analysmetoden*
- *Att genomföra en strategisk analys*
- *Att kartlägga styrkor, svagheter och jämföra dagens lösningar.*

I valet av modell för att analysera de undersökta lösningarna övervägdes också andra alternativ till SWOT-analys. Några exempel är TOWS[1], PEST[2], och SOAR[3]. SWOT valdes ut då vi tyckte att den passade bäst in a sammanhanget. Resultatet presenteras i analysdelen av *Scientific Report*, se *Analysis* sid 77.

SWOT

Analysmetoden SWOT fokuserar på fyra faktorer: styrkor, svagheter, möjligheter och hot. Dessa presenteras i en matrisform och är indelade i interna och externa faktorer där de interna faktorerna är styrkor och svagheter och de externa faktorerna är möjligheter och hot, se figur 2 nedan. Matrisen är även indelad i *Helpful* och *Harmful*. *Helpful* är de faktorer som kan hjälpa till att uppnå målen och *Harmful* är de faktorer som kan motverka att målen uppnås. Målet med en SWOT-analys är att matcha svagheter och hot med styrkor och möjligheter. Genom att bygga på styrkor, minimera svagheter, ta möjligheter och motverka hot kan SWOT användas för att belysa de åtgärder som bör appliceras på en verksamhet. I detta arbete användes SWOT främst för att belysa de brister som finns inbyggda i dagens lösningar och de hot som dessa lösningar står inför, men även för att kartlägga styrkorna hos dagens lösningar och för att enkelt kunna jämföra olika lösningar.

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[1] Threats, Opportunities, Weakness, Strength (TOWS)
[2] Political, Economic, Social, Technological (PEST)
[3] Strengths, Opportunities, Aspirations, Results (SOAR)

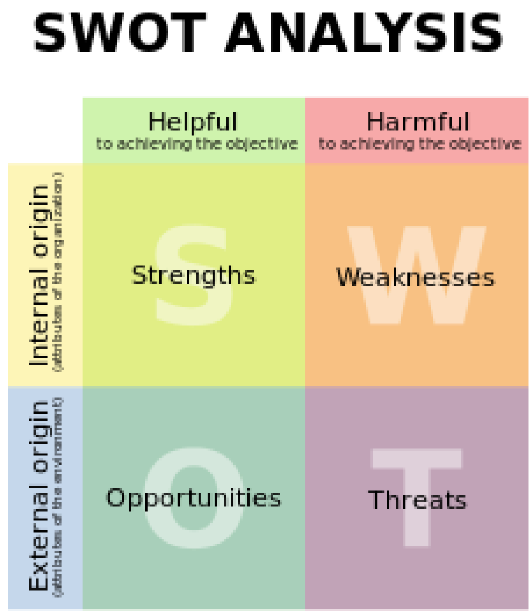

Figure 2 Bild över matrisen som användes vid SWOT-analys.

GAP

En GAP-analys syftar till att identifiera gapet mellan den nuvarande och den ideala lösningen genom att jämföra de båda åt. GAP-analysen inleds med att identifiera syfte, mål och de definitioner som krävs för att kunna analysera problemet. Därefter identifieras den ideala lösningen och utifrån den studeras dagens lösningar. Dagens lösningar analyseras var för sig. De luckor som identifierades mellan den ideala lösningen och dagens lösningar dokumenteras. Analysmetoden kan kort sammanfattas med hjälp av tre frågor:

- Vart vill vi?
- Var är vi?
- Vad är skillnaden mellan var vi är och vart vi vill?

Liksom för SWOT-analysen studerades också alternativ till GAP-analys. GAP-analys ansågs vara den bäst lämpade analysmetoden för att få kunskap om gapet mellan dagens lösningar och den ideala lösningen mot marin påväxt.

Idégeneration

Läran om att uppfinna är en kunskap som är svår att återfinna inom ingenjörsutbildningen. Dagens utbildning är inriktad på innovation. Innovation är processen om hur du överför en idé eller produkt till något som skapar ett värde (7). Innovationssystem i anslutning till Lunds universitet kan bara erbjuda hjälp om idén redan finns. Men vart kommer idén ifrån? Kunskapen om idégenerationstekniker har snarare adopterats av designers och konstnärer än av ingenjörer. Följande delmål definierades i början av arbetet:

- *Testa och undersök olika innovationsprocesser*

  För att på bästa sätt generera så många idéer som möjligt måste vi känna till en del idégenerationstekniker och – verktyg.

- *Vidareutveckla en av dagens metoder mot marin påväxt*

  Tänk utanför ramarna och kom på minst en ny och oprövad lösning mot marin påväxt.

- *Bygg upp nya metoder med teorier som stödjer dessa*

  För att vara säkra på att det är en idé värd att fortsätta med ska den vara väl underbyggd av vetenskaplig teori.

Läran om att uppfinna

Konstnärer och designers tvingar sig själva till att skapa något nytt varje dag. De löser inte bara ett problem utan skapar oftast något nytt som ingen tidigare tänkt på. Inledningsvis har just denna typ av kreatörer tillsammans med deras skapandetekniker studerats. Nedan följer några av deras berättelser. Materialet har framförallt samlats in via TED.com; en hemsida som lägger upp inspirerande och ofta vetenskapligt förankrade föreläsningar.

Filmskaparen Kirby Ferguson talar i sitt TED-talk, *Embrace the remix,* om hur nutidens stora uppfinnare inom musik och design använder sig av en teknik han kallar "Remix" (blandning). Det som är nyskapande är en fusion. Fusionen består av intryck du slagit samman och kopierat från det du hört eller tidigare sett i din omgivning. Remix är egentligen ett bättre sätt att se på kreativitet än den mer traditionella synen, att nya låtar och konstverk skulle skaps ur tomma intet menar Ferguson är fel. Vår kreativitet kommer utifrån, inte inifrån. Människan är inte självgjord utan vi är beroende av andra (8).

Joi Ito, direktör för *MIT Media Lab*, talar i sitt TED-talk, *Want to innovate? Become a "now-ist",* om en ny typ av innovation som skapats tack vare internet. Nu har du möjlighet att från första idéstadiet dela dina tankar, skapa ett kollektiv av likasinnade och nätverka. Du kan till och med generera kapital. Detta har stöpt om hela branschen. Det krävs inte längre ett stort banklån för att kunna verifiera en idé utan kostnaden för en innovation kan vara lika med noll. Man kan se det som en typ av demokratisk ”bottom up” innovation. Varje människa har idag chansen och möjligheten att vara innovativ. De innovationer som föds fram genom konkurrensen från alla andra innovationer blir på så sätt den bästa. Joi Ito säger att utbildning är vad skolsystemet gör för dig men att lära sig, är vad du gör för dig själv. Man ska istället lära sig *hur* man lär sig saker. Idag och för all framtid kommer vi att vara omgivna av internet. Fakta har således blivit lättillgänglig eftersom vi alltid är omgivna av vänner och *Wikipedia.* Det viktigaste för att lyckas med ett projekt är inte att ha hela vägen fram till målet planerad, utan handlar istället om att ha en välfungerande kompass som alltid pekar på målet. Vilken väg du tar och hur du kommer dit är inte så viktigt men vad som är säkert, om du har en välfungerande kompass och en stark vilja, är att du alltid kommer fram. Fokusera därför på att vara uppkopplade, alltid lära dig saker, var fullt medveten och närvarande (9).

I artikeln *Generating New Ideas - Think Differently and Spark Creativity* på hemsidan mindtools.com (10) definieras idégeneration som ett sätt att kombinera eller adoptera existerande idéer, precis som *Kirby Ferguson* enligt ovan talade om. Artikeln presenterar en rad effektiva verktyg men belyser att det krävs rikligt med kunskap inom det område man vill generera en idé innan verktygen kan implementeras. Samtidigt dementeras i artikeln myten om att idégeneration enbart handlar om talang. Här beskrivs det istället som en förmåga som alla kan öva upp genom att kontinuerligt ta hjälp av de presenterade teknikerna, byta ut gamla tankemönster och överväga nya perspektiv.

Relationen mellan antalet ursprungsidéer och kvalitén på den slutgiltiga idén är fastställd (11). Ju fler idéer du genererar desto bättre blir kvalitén på den slutgiltiga idén. Idag skyr de flesta människor tanken på att förlöjliga sig själv genom att tänka annorlunda och är mer direkt inställda på idéns kvalitét, istället för att fokusera på att generera så många idéer som möjligt.

En verktygslåda för att generera nya idéer

Nedan återfinns hjälpmedel och verktyg för att generera så många och så bra idéer som möjligt. Verktygen är indelade i fyra kategorier: *Bryt igenom mönster*, *Sammanför det osammanhängande*, *Byt perspektiv* och *Sysselsätt möjliggörare.*

Bryt igenom mönster

Ofta hamnar en tanke i ett mönster och det kan vara nyttigt att lära sig att bryta mönstret för att få möjlighet att tänka annorlunda. Följande strategier kan vara användbara.

- *Utmana antaganden:* Varje situation har en del huvudantaganden. Fokusera på att utmana och ifrågasätta dessa och du kommer att se nya möjligheter.

- *Omformulera problemet:* Att tvinga dig själv att formulera problemet annorlunda kommer att bidra till nya infallsvinklar. Ställ frågor såsom; Varför måste vi lösa problemet? Vad är i vägen? Vad kommer att hända om vi inte löser det?

- *Tänk baklänges:* När du är oförmögen att tänka på något nytt, prova att tänka bak och fram, motsatsen till hur du brukar tänka. Istället för att tänka på varför du måste lösa problemet, tänk istället vad du kan ha för nytta av det. Om du brottas med frågan - hur du kan göra något bättre, fråga dig istället - hur du kan göra något sämre, och så vidare.

- *Uttryck dig i olika typer av material och miljöer:* Om man byter arbetsplats eller material tenderar ens uttryck att förändras. Uttryck ditt problem genom t.ex. lera, musik eller bild och du ser per automatik andra vägar till problemet. Att försätta dig i andra miljöer låter dig också tänka annorlunda. Försök inte att lösa problemet i det här stadiet. Ta istället tillvara på alla tankar och synsätt som kommer till dig medan du jobbar med det.

- *Reflektera*: Titta igenom gamla arbeten och gångna meriter och låt dig inspireras.

Sammanför det osammanhängande

Ofta kommer lösningen till ett problem av en ren slump. Genom att befinna sig där du må höra något, se något, ofta helt annorlunda, och idén kan kläckas. Ta Isaac Newton och äpplet eller Arkimedes i badtunnan som exempel. Varför inträffade deras genombrott just där och då? De nya elementen och intrycken erbjöd ny stimuli. Du kan göra detsamma genom att försöka "sätta samman det otänkbara". Sök aktivt stimulans från oväntade ställen och se om du kan använda intrycken för att föra samman situationerna.

- *Använd slumpade begrepp:* Välj till exempel ett ord ur en ordbok. Försök gör en koppling mellan ordet och ditt problem. En fortsättning av den här tekniken är att skriva ner termer och vetenskapliga begrepp som hör samman med ditt problem och se hur begreppen kan associeras till problemen.

- *Mind map:* Sätt ett nyckelbegrepp i mitten på en tom whiteboard. Skriv första tanken som uppenbarar sig och försöka göra sammansättningar. Påminner om tekniken *Brainstorming* nämnd nedan.

- *Brainstorming:* Kallas ibland för den ursprungliga idégenerationstekniken. Metoden fungerar som så att man ska genererar så många idéer som möjligt kring ett specifikt problem. Fokus är på kvantiteten av idéer och inte kvalitén. Man får inte lov att kritisera någon idé, alla idéer är bra. Oftast är det att ju ovanligare en idé är desto större nytta har du av den. Försök att sammanföra de olika idéerna på exempelvis en whiteboard genom att kombinera dem så att de bildar en ny idé. Sätt gärna av en begränsad tid, en timme är lagom. Stäng av mobiltelefonerna och ta hjälp av ett varierat team med många olika kunskaper. En bra storlek på gruppen som utför övningen är mellan 6 - 10 personer.

- *Ta upp en bild (Forced analogy):* Gå igenom en samling bilder; abstrakta bilder eller bilder på ett tema ni har valt. Se om ni kan göra en association mellan bilden och ert problem.

- *Ta ett föremål (Forced analogy):* Fråga er själva, *hur kan det här redskapet hjälpa oss?* Eller, *vilka attribut hos detta föremål kan hjälpa oss?* Man skulle exempelvis kunna gå igenom en lista över samtliga tillgängliga laborationsredskapen vid er institution, till exempel kemi- eller fysikinstitutionen vid ert universitet.

Byt perspektiv

Allt eftersom tiden går målar du omedvetet in dig själv i ett hörn genom att till sist se saker ur ett inövat perspektiv. Just ditt synsätt skapar vissa typer av idéer. Vill vi tvinga oss själva till att tänka annorlunda måste vi vara beredda på att byta perspektiv. Ett annorlunda perspektiv är bra då det förhoppningsvis låter oss skapa nya idéer vi inte tänkt på tidigare.

- *Få en annans perspektiv:* Lämna kontoret och ge dig ut och fråga människor vad de skulle gjort om de stod inför ditt problem. Fråga dina vänner, ett 9-årigt barn, kunder, leverantörer, äldre eller någon från en helt annan kultur eller världsdel.

- *Rådfråga en expert:* Genom att tala med experter får du tillgång till deras perspektiv. Särskilt bra när man tittar på ett problem som är utanför ens kunskapsområde.

- *Rollspel:* Sätt er in i andras perspektiv genom att prova nya roller. Hur skulle du bemöta ditt problem om du var ekonomiskt oberoende, miljöaktivist, en golfare så som Tiger Woods eller din egen granne. Poängen är att de personer du föreställer dig har vissa huvudkaraktärsdrag som du tvingas utnyttja.

Sysselsätt möjliggörare

Möjliggörare är en kategori av aktiviteter och utförande som underlättar *idégenererande* genom att försätta dig i en positiv atmosfär.

- *Tro på dig själv:* Kanske den viktigaste punkten av dem alla. Tro att idéerna kommer att komma till dig. Positiv förstärkning hjälper dig att prestera bättre.

- *Sätt av tid för dagdriveri:* Ta en tupplur, en promenad eller lyssna på musik. Tillåt dig själv att leka med dina barn och ta kontinuerliga pauser från idégenererandet. På så sätt kommer du ifrån problemet och låter ditt undermedvetna arbeta med det.

- *Byta miljö:* Genom att byta miljöer byter du också ofta tankesätt. Prova att sätta dig på ett café istället för konferensrummet eller håll er planerade diskussion när du och ditt sällskap går igenom en park.

- *Konkret stimuli:* Ut och ta på problemet och känn på olika material och strukturer för att låta dig inspireras av variation och natur.

- *Stäng ute distraktioner:* Håll din tankeplats både mentalt och fysiskt ostörd. Stäng av inkommande samtal, stäng dörren och be grannen klippa gräsmattan efter att du har tänkt klart. Detta är extra viktigt desto fler ni är i gruppen.

- *Socialisera*: Ut och träffa folk för att skapa de oförutsedda mötena. Berätta för dem vad du jobbar med så föds plötsligt nya idéer.

- *Glädje och humor:* Glädje och humor är essentiella ingredienser för ett arbete när man jobbar tillsammans. Schemalägg roliga stunder där ni gör något kul tillsammans. Försök att växa tillsammans även efter arbetstid genom att göra aktiviteter tillsammans som får er att skratta.

Resultatet av idégenererande

Under arbetets gång gavs tillfällen att testa några av ovan nämnda idégenerationstekniker. Nedan följer en kort sammanfattning av varje testad teknik tillsammans med resultatet. Resultatet är definierat som antal genererade idéer på grund av den fastställda relationen: Ju fler idéer du genererar desto bättre blir kvalitén på den slutgiltiga idén.

Brainstorming Nr.1

Totalt genererades 71 idéer

Uppgiften var att komma på så många idéer som möjligt till rubriken *Lösningar mot marin påväxt*. Ju konstigare en idé var desto mer hyllningar och positiv kritik utdelades. Inga idéer är dåliga i det här stadiet och uppmaningen var att kombinera så många av idéerna som möjligt för att på så sätt föda fram nya idéer. Tiden begränsades till en timme. Gruppen bestod av två personer med samma kunskapsbakgrund.

Forced association with Role-Play

Totalt genererades 32 idéer

Under den här delen av idégenererande provades både en kombination av *Forced analogy* och *Rollspel.* En idégenerationsteknik som denna medför ytterligare en del frågor. Vad ska ens problem associeras till? Vad för bilder eller föremål föder de bästa idéerna? Du kommer redan här att ha begränsat hur du tillåts tänka beroende på vad du väljer att associera till. Även rollspelet medförde ovanstående frågor.

Rollerna som valdes ut var följande: *Miljöaktivist, miljonär, redare, kapten, glassförsäljare i Lomma, Shrek* från den animerade filmen Shrek, *Donkey* från samma film och en *alg*.

Forced Analogy gjordes till dagens rubriker på vetenskapshemsidan *www.IFuckingLoveScience.com*; en tvärvetenskaplig hemsida som skriver om det senaste inom vetenskap. Artiklarna var begränsade till det datum sidan besöktes.

Rollerna tilldelades utifrån rollistan och tidsbegränsningen var 15 minuter per roll. Rubrikerna diskuterades utifrån rollens perspektiv så länge som diskussionen upprätthölls. Därefter byttes rubrik. Detta gjordes i totalt en timme. Utifrån rollens perspektiv gäller det att försöka komma på en lösning mot marin påväxt genom skapa en association mellan ämnet och rubriken. Rubrikerna nedan var de som var aktuella 2014-07-18.

- Biological Pacemaker VS gene therapy
- The Amazon River flows backwards, and now scientists have figure out why
- Huge crater mysteriously appears in Siberia
- This guy is crazy enough to stick his hand in liquid nitrogen
- Einstein vs Quantum mechanics... and why he'd be a convert today
- Watch what happens when you stick your hand in hot ice
- Amazing photographs of Drugs Enlarged
- Turn water into ice instantly
- New super black material absorbs 99,965 % of light
- 3D touch works in 3 dimension and could replace the computer mouse
- Empty electronics factories turned into high-tech indoor farms

Miljöombyte i Lomma

Totalt genererades 45 idéer

Lomma är en hamnstad strax utanför Lund. Besöket i Lomma var i huvudsak på grund av miljöombyte och för att få känna på problemet i första person. Allt eftersom dagen fortskred användes automatiskt nya problemformuleringar till problemet med marin påväxt som påtvingade ett annorlunda tankemönster. Exempel som användes är:

- Vad är istället möjligheterna med marin påväxt?
- Om vi skulle haft en egen båt idag, hur skulle vi löst problemet då?
- Samma problem finns på land om man tänker ogräs och grusplaner. Hur löser man det där?

Brainstorming Nr.2

Totalt genererades 13 idéer

Detta var den slutgiltiga idégenereringen. Passet inleddes med att skriva upp samtliga rubriker från de mest lovande idéerna som kommit fram under arbetets gång. Uppgiften var sedan att koppla samman dessa med helt nya idéer. Sessionen varade i 30 minuter. Gruppen bestod av två personer med samma kunskapsbakgrund.

Under samtliga pass skrevs alla idéer ner och kategoriserades. Under ett gemensamt möte plockades de mest lovande idéerna ut. Det var de idéer som ansågs ha mest potential och vara så nära en ideal framtida lösning som möjligt. Totalt valdes 9 idéer ut och redovisas i *Scientific Report,* se *Future Ideas* sid 88. Dessa följdes upp med djupdykning i idéernas bakomliggande teorier så att de kunde stödjas med vetenskapliga argument.

Utvärdering

Från början av arbetet var det ett mål att återkoppla och utvärdera arbetet. Reflektion för ett arbete handlar bland annat om att analyserar vilka metoder och tekniker som fungerat bra respektive mindre bra och vad som kan göras bättre. Nedan följer vår utvärdering från olika delar av processen till arbetet och om hur dem utfördes. Följande delmål definierades:

- *Studera metoder och teorier för återkoppling och utvärdering.*
- *Värdera de olika typerna av innovationstekniker.*
- *Diskutera vår framtida metod mot marin påväxt med experter.*

En bra utvärdering ska sammanfatta förloppet av arbetet och jämföra resultatet med de satta målen. För att visa hur arbetet har utvecklats över tid gäller det att kontinuerligt samla in information om hur arbetet fortskrider. Detta ska göras i början, under tiden och efter arbetets slut. En utvärdering börjar tidigt, samtidigt som planeringen till arbetet görs. Om målen för arbetet görs *SMARTa* blir utvärderingen bättre. Det vill säga mål som är *Specifika, Mätbara, Rimliga* (Achievable), *Relevanta* och *Tidsbundna*. Säkerställ därför att de satta målen är mätbara och bestäm hur de ska mätas. Skapas mål som är enkla att mäta kan de snabbt och enkelt jämföras med resultatet. Samtidigt kan arbetets utveckling lättare följas med tiden. Ett exempel är antalet företag som svarar på mejl jämfört med antalet utskickade. Det är klokt att inledningsvis ta hjälp av en eller flera personer som kommer att vara med under hela arbetet. Dessa kan efter arbetets slut tillfrågas om vad de tyckte och om arbetet levde upp till deras förväntningar (12, 13).

Före en utvärdering är det bra att ställa följande frågor till sig själv:

- Vad är meningen med utvärderingen och vad skall den visa?
- Vem är utvärderingen för?
- Vad ska utvärderas och vilka delar av arbetet skall belysas?
- Hur ska utvärderingen utföras och behövs utomstående personer kontaktas?

Välj vilka delar av arbetet som ska utvärderas och ställ följande frågor för att ta reda på om och hur väl målen har uppfyllts (14):

- Har målen blivit uppfyllda?
- Vilka är de viktigaste resultaten?
- Har projektet någon mätbar effekt?
  Till exempel, antalet besökare på Lunds Lasershow efter en reklamkampanj i Sydsvenskan.
- Var valda arbetsmetoder effektiva?
- Vilka lärdomar finns?
- Vad skulle gjorts annorlunda?

Är arbetet stort med många delar att utvärdera gäller det att prioritera frågorna i mån av tid. Frågorna som slutligen fick störst fokus var*: ”Var valda arbetsmetoder effektiva?”, ”Vilka lärdomar finns?”* och ”V*ad skulle gjorts annorlunda?”.* Utvärderingen delades upp i följande delar: *Litteraturstudie, Möten, Idégenerationsfasen, dokumentation* och *analys.*

Litteraturstudie

Den utförda litteraturstudien uppfyllde de delmål som var satta. Litteraturstudien gav lärdomar i hur du utan områdeskunskaper sätter dig in i ett nytt forskningsområde. *Hur börjar man? Hur ska man lägga upp sitt arbete?* och *Hur vet man vad som är relevant?* är alla frågor vi nu kan besvara. Andra kunskaper och tekniker som har förvärvats i och med litteraturstudien är hur du snabbt sätter dig in i artiklar, skapar dig en överblick och värderar innehållet i artiklarna. Insikten om att du inte kan läsa dig till allt blev också uppenbar under våra besök hos industrin. Att lämna litteraturen hemma och komma ut i verkligheten är väldigt viktigt för att komma vidare med sina litteraturstudier. Under mötena med industrin kunde läst material valideras, svåra uttryck bli förklarade och historier från deras år av personlig yrkeserfarenhet bli insamlade. Dessa är alla saker en bok har svårt att skildra. Vi insåg att den tvärvetenskapliga bakgrund vi fått under vår grundutbildning inom teknisk nanovetenskap gett oss en allmänkunskap om nästan samtliga vetenskapsområden vi stötte på under arbetets gång samt gett oss en god vana möta nya vetenskapsområden.

Litteraturstudien och framför allt litteratursökningen hade en lång startsträcka. Detta då vi inte hade någon förkunskap inom marin påväxt. Det saknades uppfattning om nyckelbegrepp och en tydlig bild över vetenskapsområdet. Detta gjorde att vi inledningsvis inte visste vad vi behövde lära oss. Det hade säkerligen gått snabbare om någon med ämneskunskap hade funnits att tillgå. Troligtvis hade detta inneburit att vi lärt oss mer om marin påväxt på kort sikt men blivit påtvingade samma mall och perspektiv som andra inom vetenskapsområdet. Istället fanns fördelen att ämnet bemöttes med ett helt nytt perspektiv, nämligen vårt. Samtidigt hade vi missat många lärdomar under arbetets gång om vi gjort på ett annat sätt. Vi är båda överens om att vi inte hade velat utföra litteraturstudien på ett annat sätt, även om det gjorde att vi inledningsvis fick lägga två till tre veckor på att bara lära oss grunderna. Att ämneskunskap om marin påväxt inte fanns på Lunds universitet var något vi visste från början och blev därför något vi tvingades att jobba runt.

Under den inledande delen av arbetet ansågs det att artiklar som var äldre än 5-6 år var för gamla för att uppmärksammas. Nya och mer välciterade artiklar borde ha blivit publicerade under denna tid. Efter en viss tids arbete drogs slutsatsen att antagandet var felaktigt. Sjöfartsnäringen och industrin som arbetar med marin påväxt är en långsam bransch, där det ofta går 5-6 år innan ny teknik prövas. Det tar därför lång tid för ett publicerat forskningsresultat att bidra till en förbättrad eller ny produkt inom fartygsbranschen. Detta gjorde att vi fick omvärdera vår urvalsprocess.

Något som vi försökte, men misslyckades med, var att tidigt i arbetet komma ut och samtala med industrin. Syftet var att lära oss så mycket som möjligt om marin påväxt och få bekräftat teorier och begrepp som vi läst om. Ett sådant besök skedde aldrig. Det berodde delvis på att kunskapen om vilka aktörer som fanns inom marin påväxt förvärvades under lång tid. Det hade varit bra för arbetet att komma ut i industrin i ett tidigare skede även om våra kunskaper var begränsade. Vi gjorde två besök och samtliga var under arbetets sista hälft.

Dokumentation

Saker som i efterhand borde gjorts annorlunda är dokumentationen av sökprocessen. Den var ineffektiv och för tidskrävande. För att dokumentationen av sökprocessen inte ska hämma litteratursökandet krävs det en metod som låter dokumentationen ske parallellt med sökandet. Efter varje sökning skrevs all data in i ett Excel-ark. Detta tog tid från sökprocessen och det var till och med så att det uppstod en tvekan inför varje ny sökning till följd av det extraarbete som dokumentationen innebar.

Vid dokumentationen försökte vi att värdera litteratur utefter om den var läsvärd eller skulle förkastas. Värderingen av artiklarna var särskilt svår i början av arbetet när ämneskunskap saknades.

Möten

Kontakten med industrin och akademin motsvarade inte våra förväntningar. När projektet inleddes fanns förhoppningar om betydligt fler fysiska möten än endast de två som genomfördes. Trots detta skapades kontakt med flera inflytelserika personer och företag inom området. Sommarens semestrar försvårade processen med att boka möten. Det område vi framför allt har haft svårt att komma i kontakt med är de faktiska kunderna, det vill säga rederierna. En telefonintervju ägde till sist rum med rederiet Wallenius Lines, detta på den allra sista dagen av arbetet. Wallenius kunde besvara frågan om hur dagens lösningar mot marin påväxt verkar och vad de önskar av en framtida lösning. Fler rederier måste tillfrågas om vad de vill se för lösningar för att få en representativ bild från branschen.

För att spara tid och lättare få kontakt med rätt person inom ett företag har vi insett att det inledande mejlet bör vara kort och målinriktat. När kontakten väl är etablerad är det bättre att skriva ett mer utförligt mejl som berättar *vem du är*, *vad du vill* och *varför du kontaktar just dem*. Att skriva mejl till företag var ofta tidskrävande då mycket stod på spel och vi var måna om att få dem bra.

Vi lärde oss snabbt att allt handlar om att få tag på rätt person och bygga vidare på den nyskapade kontakten. Under mötet med biocidföretaget *i-tech* bekräftade de att bra kontakt med kunderna var rätt tillvägagångssätt för att inhämta kunskap om dagens lösningar mot marin påväxt.

När kontakten med aktörer inom marin påväxt väl var etablerad var de ofta väldigt hjälpsamma och positivt inställda till vårt arbete. Dessa kontakter gav oss möjlighet att få svar på ämnesrelaterade frågor och funderingar.

Slutligen måste värdet av det inofficiella belysas eftersom det är just där som kontakter med aktörer ofta skapas. Du når inte alltid längst av att vara sakkunnig och intresserad av ett område utan du måste också vara trevlig och tillmötesgående. Något som är viktigt för att bygga långsiktiga kontakter.

Analys

Värdet av att kunna ta ett steg tillbaka och analysera situationen och arbetet var en lärdom för oss båda. Tiden som SWOT- och GAP-analysen utfördes på var för kort. Kvalitén på analysen kunde blivit bättre om den utförts under en längre tid. Då tidigare erfarenhet saknades inom de genomförda analysmetoderna hade det varit givande om en person med tidigare erfarenhet hade funnits att tillgå. Någon som kunde dela med sig av tips och idéer för hur man gör en så bra analys som möjligt.

Idégenerationsfasen

Den kreativa delen av arbetet var kanske den absolut roligaste men tog förhållandevis mycket tid. Att jobba med den kreativa processen parallellt med arbetet hade varit mer effektivt.

Genom att ta hjälp av människor från olika bakgrunder och med olika kompetenser hade den kreativa processen kunnat nå ännu längre, något vi tyvärr inte hade möjlighet att prova. Att utöva *Brainstorming* i en större grupp hade också varit givande.

En annan viktig idégenerationsteknik är att socialisera och att försöka skapa oförutsedda möten. Här kunde vi utnyttjat Internet som är ett av dagens bästa verktyg för att skapa kontakter. Ett exempel skulle kunna vara att ställa frågor kring marin påväxt på ett par välkända forum och att försöka föra samman människor som har ett gemensamt intresse för frågan, likt det *Joi Ito* pratade om i sitt TED-talk (Se idégeneration, *Läran om att uppfinna* ovan*).*

Insikter från arbetet

Lärdomarna och insikterna till följd av arbetet är många. En insikt som starkt har påverkat arbetet är att allt tar längre tid än man tror. Den projektplan som arbetet utgick från fick redigeras varje vecka. Anledningarna till detta är främst att det tog betydligt längre tid att inhämta den kunskap som behövdes för att skapa sig en tillräckligt god vetenskaplig grund inom området. Att komma i kontakt med företag och institutioner tog också längre tid än väntat.

Synen på problematiken förändrades ju mer ämnet studerades och våra uppfattningar färgades allt mer av de generella åsikterna som finns inom fältet för marin påväxt. Då målsättningen var att se problemet med öppna ögon och i en förlängning tillföra branschen något nytt, var det viktigt att inte låta de generella åsikterna påverka oss.

Rapporten kommer främst att lämpa sig för studenter med en bakgrund inom kemi, fysik, biologi och med ett intresse för marin påväxt. Troligen är rapporten inte lika angelägen för redan ämneskunniga, som var ursprungsidén, eftersom den har ett begränsat vetenskapligt djup.

Uppdelning av arbetet

Arbete har fått en naturlig uppdelning efter processens gång där intresse och tidigare kunskap har styrt uppdelningen. För att göra det effektivare och undvika dubbelarbete har förhållandevis stora delar av arbetet delats upp mellan författarna enligt följande:

Processen

Litteraturprocessen

- Undersökning inför litteraturprocessen — Niklas
- Genomförande — Niklas & Erik

Mötesdelen

- Planerat och ansvarat för kontakt med majoritet av företagen — Erik
- Ansvarat för dokumentationen — Erik

Idégeneration

- Undersökning och planering — Erik
- Genomförande — Niklas & Erik

Utvärdering

- Undersökt och ansvarat för utvärdering av arbetet, — Erik
- Genomförande — Niklas & Erik

Scientific Report

Biologi — Niklas & Erik

Bioinspirerade Solutions — Erik

Antifouling Today — Niklas

- Biocides
- Experimental methods

Analysis

SWOT

- Undersökt och ansvarat — Niklas
- Genomförande — Niklas & Erik

GAP

- Undersökt och ansvarat — Niklas
- Genomförande — Niklas & Erik

Future Ideas (Dessa har delats upp mellan författarna enligt följande)

Niklas

- UV as Disinfectant
- Titanium Dioxide and UV-light
- No Hard Surface
- Conductive Paint
- Hull Cover

Erik

- Electric Field
- Coating with UV-light
- Affect the hull with outside force
- Surface affected by stimuli

Discussion Niklas & Erik

Scientific Report

Introduction

The growth of marine organisms on submerged structures has been known since mankind first set sail. A written record from the 5th century has been found telling about the first treatments for marine vessels (15). The unwanted growth and colonization of submerged structures are called marine fouling and results in increased drag on ship hulls. To minimize the increase in drag, a wide range of different antifouling methods have been developed with different results. An early solution in modern time using TBT (tributyltin) showed very successful results in reducing the fouling, but little was initially known about its toxicity. TBT was later described as the most toxic substance ever deliberately introduced into the marine environment (16) and in 2008 the international maritime organization (IMO) banned all use of TBT (17).

A heavily fouled ship hull may result in a decrease of up to *86 %* in powering penalties at cruising speed and even light fouling from “slime” may cause a decrease of *10-16 %* (18). This makes it crucial to tackle the problem to reduce the fuel consumption in an efficient way and reduce polluting exhaust emission. According to S.M. Evans et al. (16) some of the world’s most polluting exhaust per ton used fuel, is emitted from the type of diesel used by *95 %* of the merchant shipping fleet.

The legislation and ban of some biocides in recent years have increased the interest in the fundamentals of fouling and the development of new methods to reduce the effect of fouling. Alternatives to antifouling methods are so-called foul releasing techniques. Instead of preventing the organisms to settle, the surface has a very low surface energy that makes the organism attach very loosely and loosen by the force from the moving water. Much is still left to be done before we will see a solution that has a hydraulically smooth surface, lifetime fouling protection, is environmentally friendly, limits the invasion of invasive species, is easily applied, repaired and maintained, is compatible with the materials and methods used for hull construction and decommissioning, and is cost effective.

This part of the report aims to present a brief overview and an up to date summary of methods used and researched to tackle the problem with marine biofouling. To do so, a short introduction to the problem, the organisms and the process of fouling, will be presented. Today’s antifouling solutions will be analyzed and their strengths and weaknesses presented together with a GAP analysis. The authors’ thoughts about possible alternative solutions to the problem will also be presented.

Factors influencing marine fouling

The process of marine fouling is dependent on the substratum, geographical location, the season and competition from other species and predators (18). Coastal areas are more heavily fouled, fouling also depends on the temperature and higher temperature areas are more severely fouled. Factors that also affect the fouling are salinity, pH and nutrition levels in the seawater. Examples of areas that are especially heavy fouled are Singapore and Brazil (19).

Fouling on ships is affected by several factors such as the type of ship, the cruising speed, the idle periods and the traveling routes (19). Lower speed exposes the ship to more fouling and ships are especially exposed to fouling when idle (20, 21). Vessels that are idle for long periods can accumulate a large amount of biomass (22). Depending on the traveling route the ship is exposed to areas with different fouling levels. These factors have to be taken into account when fouling protection is selected (15).

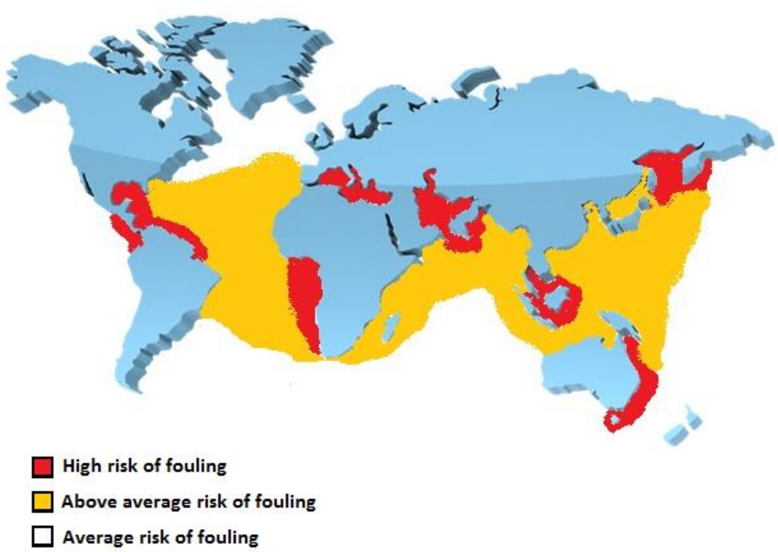

Figure 3 Illustration showing the risk of fouling for different geographic locations.

Fouling - The problem and the organisms

Biofouling is the process in which living organisms attach to and colonize hard surfaces (23). Marine fouling is a type of biofouling concerning the fouling process in the water column of the sea. Hard bodies come in different types. Some are made by the nature and some are made by man. According to Simone Dürr et al. (23) the hard bodies can be divided into three different groups: *Non-living natural substrate, living organism* and *man-made structures*. We will in this report focus on the biofouling on *man-made structures*. These types of structures are rather heterogeneous and therefore need to be protected by different types of antifouling (AF) methods to avoid fouling (23). A hard substrate is often the limiting factor in an otherwise favorable environment, one can understand why fouling occurs on immersed structures (24). An ocean full of life, just waiting for something to come by to settle on, to be able to grow, reproduce and thus, fulfill their life cycle.

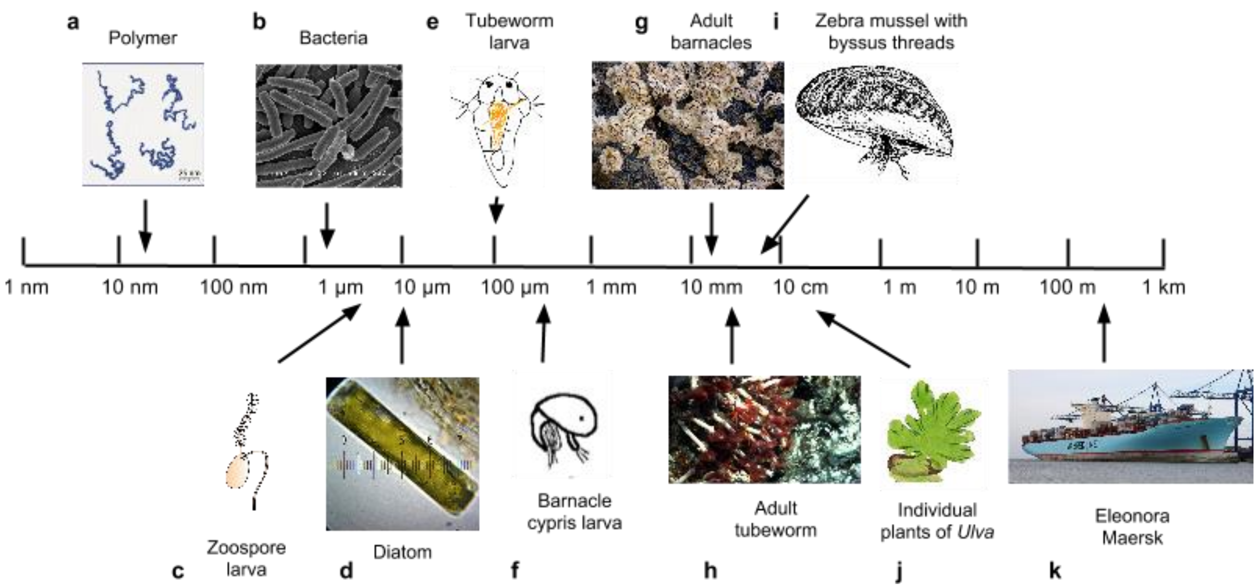

Figure 4 Diversity and the complex size scale of a range of representative fouling organisms and a man-made structure. (a) Polymer seen through atomic force microscope (AFM), (b) bacteria, E. coli, (SEM), (c) illustration of zoospore larva, (d) diatom, light microscope (e) an illustration of a tubeworm larva, (f) an illustration of a barnacle cypris larva, (g) adult barnacles on a hard surface, (h) adult tubeworms submerged in water, (i) an illustration of a Zebra mussel with byssus threads, (j) an illustration of individual plants of green algal, Ulva, growing on a rock, (k) an example of a 400 meter long container carrier, the Maersk ship Eleonora.

The colonization of submerged structures is reported to involve over 4000 species (2) of organisms from bacteria, diatom, algal and spores to barnacles, tubeworms, oysters and mussels (18). A distinction between the different fouling organisms based on size and shell structure is often made. The first group of fouling organisms is referred to as *Microfouling* and consists of unicellular microorganisms like bacteria, diatoms and protozoa. These microorganism make up the most primitive of lifeforms and are found in abundance in the ocean. They colonize surfaces through formation of biofilms and might be referred to as either thin or thick slime, depending on its thickness. *Soft macrofouling* includes macroscopically visible alga (like seaweed) and invertebrates. The last group is referred to as *hard macrofouling* and is composed of shelled invertebrates like barnacles, mussels and tubeworms (18). Many people know them from covering the poles of piers or have seen them on rock sides in tidal areas. They are found in less abundance in the ocean compared to microfoulers and tend to be more selective when choosing settling place. But their sheer size (see Figure 4 for scale) has a huge impact on drag penalty on ship hulls if they chose to settle.

A dynamic process

It has long been stated that the process of biofouling is a linear process where the second step is dependent on the first, proposing that macrofoulers can't colonize a surface until weeks after microfoulers have had their turn, illustrated in Figure 5(a). In reality, this 'classical' model, one that still might be the public opinion, is a rough oversimplification. In reality, it is a much more dynamic process where larvae of barnacle, bryozoans, hydroids and other species of macrofoulers have been reported to settle within hours after immersion (25) on a clean substrate. Thus, the dynamic process is a better interpretation of reality, see Figure 5(b). When introducing a clean surface to natural seawater it soon starts to adsorb a molecular film of mostly organic material (18). The continuous colonization is done by a wide range of organisms (both micro- and macrofoulers) depending on what organisms exist in the surroundings. It is also erroneous to believe that preventing one step in the fouling process will cancel the next, e.g. stopping the biofilm formation will not stop the hard macrofoulers to settle.

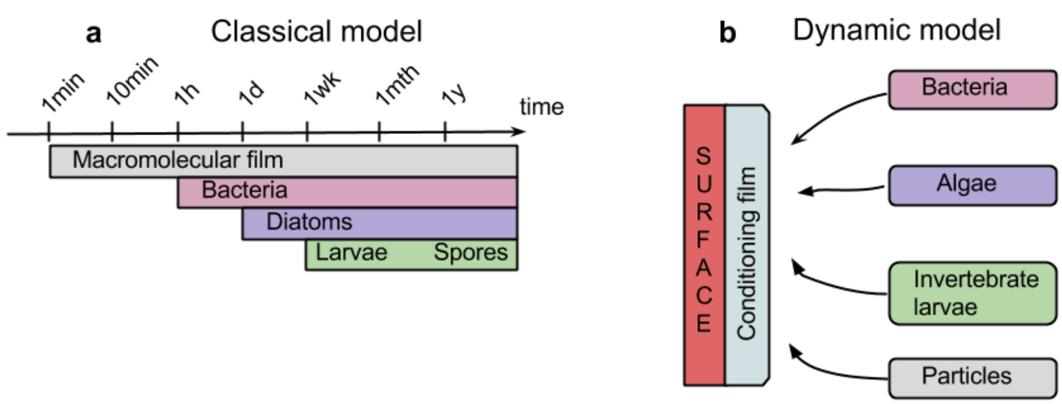

Figure 5 (a) the classical model. The settlement of foulers is a step by step processes, where the second step is dependent on the first. I.e. Larvae can't settle until one week after immersion and requires diatoms to be a pre-colonizer. (b) The dynamic model describes the settling organisms to be independent of one another, some organisms can settle only hours after a substrate has been immersed (25).

The Life Process

The life process of fouling organisms, both micro- and macrofoulers can be described in the following order: transport, settlement, attachment, development and growth (26). For some groups, for example, microorganisms, the process might be shorter where the development and growth, may instead be interpreted as population growth (by increasing biomass i.e. through cell division). Dispersion of foulers have long been thought to be a passive process, meaning they lack the ability to affect direction of their gametes (e.g. sperm cell or egg cell) or propagules (e.g. seeds and spores). Gametes or propagules are released from species in order for them to reproduce. Research tells that the species bosses some ways to affect their direction. By timing of tidal movements or seasonal influences, species' dispersal can be strongly influenced and thus increase their chances of survival. The process of settlement can be described as the process of movement towards a hard surface, contact with it, exploration, evaluation, and selection or rejection of the substrate (23).

Settlement

The process of settlement is the most basic event for any organism when encountering and attaching to a hard surface. Important to notice is that the settlement process is only one stage in an organism's life cycle. When the organism settle and the metamorphosis is complete, the fouling organism is immobilized. For the process of biofouling, this transition is in focus and it is believed that the organism's adhering to hard surfaces is the weakest link in the biofilm formation (27).

The first general step for an organism to settle on a substrate is to encounter a surface possible to attach to. This encounter can occur in three different ways according to Simone Dürr et al. (23). The following descriptions are cited from his book, *Biofouling.*

- *Basic model* **-** only hydrodynamics and surface properties entrain inert planktonic propagules, presumably mechanical contact triggers settlement reaction.

- *More complex* **-** propagule involuntarily responds to environmental stimuli e.g. chemical triggers stimulate the settlement response.

- *Most complex* **-** propagule actively seeks out and choose the best settlement site using behavioral responses to environmental cues.

The encounter strategy also responds to the energy investment in each propagule. Less investment in each propagule, like the basic model propose, is balanced with a huge number of propagules to increase its chances of success. The more complex method i.e. bigger energy investment means more knowledge about the substrate and likelihood of beneficial settlement for each of the settlers.

Microfouling - Biofilm

Microfouling is often referred to as the slime on ship hulls or other submerged structures and is consisting of unicellular microorganisms like bacteria, diatoms and protozoa that together form a biofilm. Depending on its thickness, it is either described as thin or thick slime. Not as much research has been done on micro- as on macrofouling. The reason is thought to be that the economic effect, due to microfoulers increased drag on vessels, wasn't firmly established until recently (18).

Molecular film

Molecular film or biochemical conditioning describes the adsorption of dissolved chemical compounds to any surface after immersion in seawater. It is mostly macromolecules like glycoproteins, proteoglycans and polysaccharides that occur naturally. The accumulation of organic molecules at interfaces is purely physical and 'spontaneous'. What happens is that you lose the randomness of molecular distribution, meaning that you get a decrease in entropy, resulting in a notable diminution of the total free energy of the system. Thus the phenomenon replaces the high energy solid/liquid interface by a lower energy organic layer. Their physical and chemical surface properties converge so that low-energy (hydrophobic) surfaces experience an increase and high-energy (hydrophilic) surfaces experience a decrease of their gamma-values (surface free energy). The adsorption of macromolecules is a process that starts within seconds after immersion in seawater and has reached equilibrium after a few hours (24).

The forming of the organic layer is a very fast process which is not necessary for the adhesion and settlement of other foulers (28). After interaction with the surface, microorganisms adhere and secrete extracellular polymeric substances (EPS). This step is often considered irreversible and eventually, after growth and cell division, leads to a completed biofilm (29). The attachment process for diatoms is much more complex than that of bacteria. It requires glycoprotein and protein synthesis as well as metabolic energy, meaning it is far from a passive process.

Investigations of the means by which marine microorganisms adhere to surfaces have been of interest for the last 50 years. Yet, we still do not completely understand the mechanisms involved.

Bacteria

It was long thought that bacteria was one, or rather the, initial colonizer. One kind of bacteria, the *Vibrio proteolytica* for example, have two unique attachment mechanisms; one for each kind of a surface, being either hydrophilic or hydrophobic. K.E Cooksey (28) make the interesting suggestion that cells may possess multiple mechanisms of adhesion and utilize whichever is appropriate depending on the surface energy of the substratum. An experiment conducted by K.E Cooksey (28) with three different kinds of bacteria whether they preferred low or high surface energy showed that all had different responses. Motile bacteria for instance, once attached to a surface their motility either is reduced or they become stationary. An exception is made for the so-called 'gliding bacteria'. K.E Cooksey (28) found that gliding was inhibited on surfaces of very low surface energy and 'skittish' i.e. appeared uncontrolled, on hydrophilic surfaces. Gliding is in some degree a way for the cell to interact with the surfaces physiochemically and it is probably mediated by some kind of extracellular polymer.

Diatoms

It is estimated that there is over 10 000 different species of diatoms but only a few, eight to ten, that have been commonly documented to cause a problem for modern fouling release or antifouling coatings (30). On metal and alloy surfaces, diatoms are often the dominating organisms in the biofilm (29).

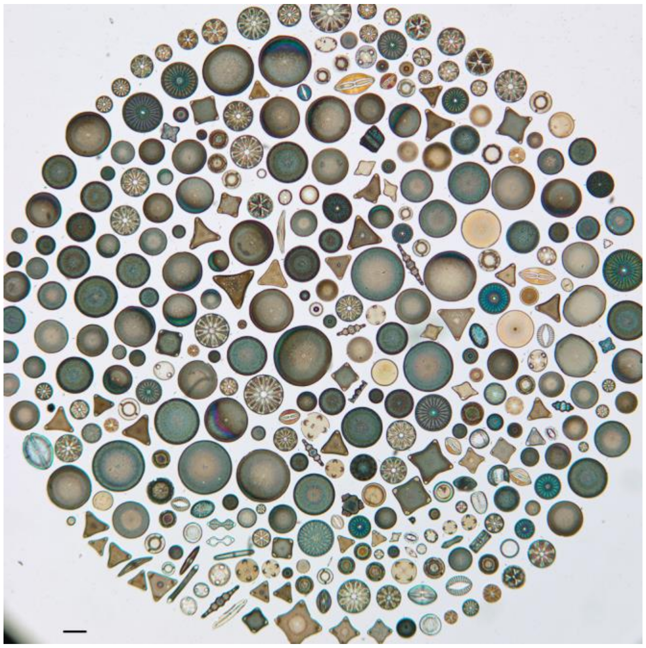

Figure 6 An example of how varied diatoms species are. This photograph shows fossil diatoms collected in Pt. Reyes National Seashore in Marin County, California, USA. The scale bar is 100 micron.

Diatoms are a type of algal and have a siliceous skeleton called frustule. They are non-motile and only capable of limited motion by secretion of mucilaginous material through a channel called raphe. This motion is limited to a surface (31). The size of diatoms vary and some can be up to 2 millimeters long. Commonly, they are between 20-200 μm in diameter or length. Diatoms can live in long chains attached by mucous filaments. Large numbers of filaments can form sediments composed of almost only frustules which can be used in for example filters, paints and toothpaste. The diatoms are sensitive to their environment and have specific salinity and temperature tolerances (31).

Macrofouling - Soft and hard

To describe the settlement strategies of macrofouling, three major macrofoulers will be analyzed: mussel, barnacle and algal, with the focus on their early settling stages. These ones are selected since they are investigated in many articles and are viewed as some of the major macrofoulers.

Soft macrofouling

The alga *Enteromorpha*, part of the Ulva family, is the green, grass-like alga that can be found on rocks along the shoreline. The first step towards settlement for the zoospores is to swim close to the surface (32). Almost all algal (except red alga) zoospores have a flagella that is used for movement and for sensing the surface during pre-settlement explorations (33). When the algal approach the surface it decelerate (32). For the green algal *Ulva Linza* and the brown algal *Hincksia Irregularis*, the interaction with the surface also induces a motion called gyration, which can be described as intense exploration during an occasional surface contact (32), meaning they look for the most suitable place to settle. The gyration can result in two processes, *hit and run* which is a process in which the algal leave the surface or *hit and stick.* The last process results in the algal to stop swimming and stick to the surface (34). This process, in which the algal stick, is not the same as settlement due to the fact that the algal neither have secreted permanent adhesive nor retracted their flagella (34). Instead, sticking refers to that the algal stays motionless on a specific point on the surface. If the algal stick to the surface, soon after a spinning motion has begun, the spinning process can last several minutes (35). Depending if the spores are able to hold on to the surface, this step will determine if they settle on the surface or not. Less than 5 % of the spores settles permanently (32). The duration of the spinning process is determined by the surface chemistry. If the algal settle on the surface, the flagella is withdrawn and a cell wall develops, followed by adhesive material released from its vesicles. The adhesive durability to the hard surface increases as the algal grow (23).

The most common macroalgae, for fouling on man-made structures, belongs to the genus *Ulva*. Studies of the *Ulva* zoospores showed that electrostatic interactions affected initial adhesion when settle on charged surfaces. The zoospores are negatively charged and were less willing to settle on similarly charged surfaces than on neutral or positively charged surfaces. The adhesive strength was also greater on neutral and positively charged surfaces (35). *Ulva* algal are sensitive to a range of different cues when choosing where to settle. Negative phototaxis guides zoospores to areas with low light, together with diffusible chemicals that are released from surface-associated organisms (36). Settlement is also dependent on surface properties such as wettability and microtopography.

Hard macrofouling

Barnacles

Much attention has been pointed toward barnacles due to a couple of reasons, one is that it is the only crustacean to live a sessile existence. It has also become a model organism for laboratory-based studies because of its short reproduction cycle and easy handling in laboratories. This, combined with the fact that it is one of the dominating foulers, makes it a key organism to study.

To get a basic understanding of the barnacle it is good to first study its life cycle illustrated in Figure 7. Once a cyprid larva the barnacle is non-feeding and, therefore, needs to find a place to settle before its energy reserve is depleted. To do this, the cyprids are equipped with an antennule having mechanical and chemical receptors (35). This allows the cyprids to probe the surface by using temporary attach points which result in something that resembles a walk. When walking on a surface the cyprids leave footprints of glycoproteins (35). When content with its location the cyprids starts its attachment process by secrete cement that adheres the cyprid to the surface permanently. By doing so, the barnacles goes from a planktonic to a sessile life stage. It has been showed that cyprids, when exposed to micro-texture surfaces tend to avoid that surface and spend more time exploring soft surfaces, opposed to flat surfaces. Also, they rather settle on hydrophilic than hydrophobic surfaces (37).

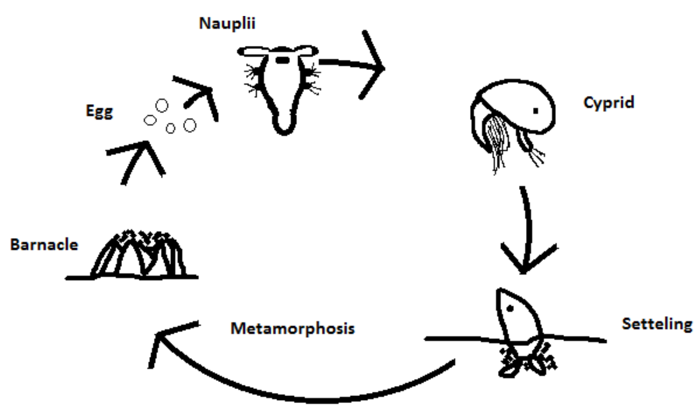

Figure 7 An illustration showing the life cycle of barnacles.

Mussel

Mussels differ from other foulers due to their ability to voluntarily detach and find a new place to reattach. It does so by secreting threads known as byssus from glands located in the foot organ. Attached to the foot organ are so called mussel foot proteins (mfps), these have a function as cohesion of the byssus and binding to minerals and metal oxide substrates (36, 38).

Bioinspired Solutions

Ship hulls are not the only surfaces in the ocean that need to fight marine organisms. It might be obvious, but there are no barnacles on a shark's body or no seaweed on codfish. After years of evolution, marine animals have found their own way of preventing marine fouling. Today, a lot of research is dedicated to studying nature and mimic its behavior, something known as biomimetic or bioinspiration. Biomimicry refers to the mimicking of life, imitating biological systems (39). Bioinspiration refers to solutions inspired by nature. Not only mimicking biological systems but also trying to improve them. In this section, we will take a closer look at nature's solutions on marine fouling and see if any solution could be implemented together with today's technology, or, lead up to a novel solution.

Marine animals and plants have evolved several different techniques to avoid fouling. These natural antifouling solutions include chemical, physical, mechanical or behavioral responses. The challenge is not in itself to study nature, but rather, selecting the most effective and reproducible antifouling mechanisms to study, which also could provide a realistic, engineered solution (40).

Naturally occurring antifouling

The following antifouling methods are found in nature.

Chemical

Chemical substances found in nature, with antifouling properties, have for a long time been the subject of extensive research. To date, thousands of active compounds have been identified. Substances with properties like lowering the pH, deterrent effects, anesthetic properties and metamorphosis inhibiting (40).

The most well documented red alga is *Delisera pulchra.* It is effective in deterring growth of both micro- and macrofouling. On its surface is present the halogenated furanone in concentrations that are enough to chemically prohibit fouling. However, the long studied chemical has not yet been successfully incorporated into a long-lasting coating (40).

Looking at terrestrial plants for solutions have showed promising results. One example is the substance pyrethrin, derived from the chrysanthemum flower. *Pyrethroids*, that is a synthetic analog of pyrethrin, has already been approved as an environmental friendly insecticide. Pyrethroids show low toxicity to mammals, do not bioaccumulate and are available in industrial scale, reasons why the substance deserves attention.

Another example is the substance *tannin*, present in mangrove trees. The chemical is anti-herbivory and tend to have antifouling properties (40).

Algae, sponges, corals etc. have in the past been known for their antifouling metabolites. A closer study showed them to be produced by surface-associated bacteria and cyanobacteria. Microorganisms like these could be used by either isolating the active chemical or by being directly incorporated into coatings. There are many benefits of using microorganisms to produce chemicals. One is their abundance, and another is the ability to trick or stress them to produce larger quantities of the desired chemical (40).

The use of enzymes and hormones is yet another way with the potential to inhibit some of the fouling. By focusing on substances already on the market some patents have been awarded, although their effectiveness is not always backed up with scientific evidence. *Noradrenaline*, a neurotransmitter and hormone, may also be used for its non-toxic deterrent in antifouling coatings. Even if it has favorable abilities noradrenaline is a perfect example of the difficulties and drawbacks with this kind of substances in paint. It is expensive, unstable and needs environmental approval before implementation (40).

Physical

Physical and 'physical means' refers to the surface of the marine animal. The surface texture and the surface energy have been identified as the main surface properties influencing fouling. These are both properties that marine animals have adapted and refined in order to minimize the fouling, a process that has evolved over millions of years through evolution. Killer whales, gorgonians and even healthy teeth have all been measured to have a surface energy of *20-30 mN/m*, an energy that has been shown to minimize adhesion and favor removal of epibionts. Surface energies play a bigger role than previously anticipated and it is one of the reasons why the problem with marine fouling is so complex. It has for example been shown that barnacles and bryozoans prefer to settle on different surface energies. Not to mention diatoms and the green algal Ulva that have opposite adhesion strengths depending on surfaces having different wettability. Diatoms are more easily removed from hydrophilic surfaces and Ulva are more easily removed from hydrophobic surfaces (40).

Surface topographies play an important role in a marine animal's antifouling properties. In the last years, more focus and attention have been given to the subject. This is due to the fact that scientists are starting to find more and more marine animals' dependence on specialized surface topography as part of their antifouling protection. The effectiveness of a surface topography appears to be the relationship of scale between the texture and the settling organisms. An ultra-smooth surface for instance, does not offer any refuge from predation or hydrodynamic stresses and is, therefore, an unattractive surface for a microorganism (40), meaning, there is nowhere to hide either from predators or fast moving water flows.

Textures with variable sizes might either reduce or increase fouling on micro textured surfaces. This is called the *attachment point theory* and is illustrated in Figure 8. The attachment of a settling organism is increased when there is an optimal number of 'potential settling points' (meaning 'attachment points') and reduced if few points of attachment are offered (41). The number of attachment points is from the settling organisms' perspective. If fouling organisms or their attachment instruments are larger than the scale of microtexture they will have reduced adhesion. Fouling organisms that are smaller, than the scale of microtexture experience the opposite, meaning they get more strongly attached due to more 'attractive' topographies (42). Barnacles, for instance, have only one attachment point and are, therefore, more specific in their search for a high-quality attachment point (40).

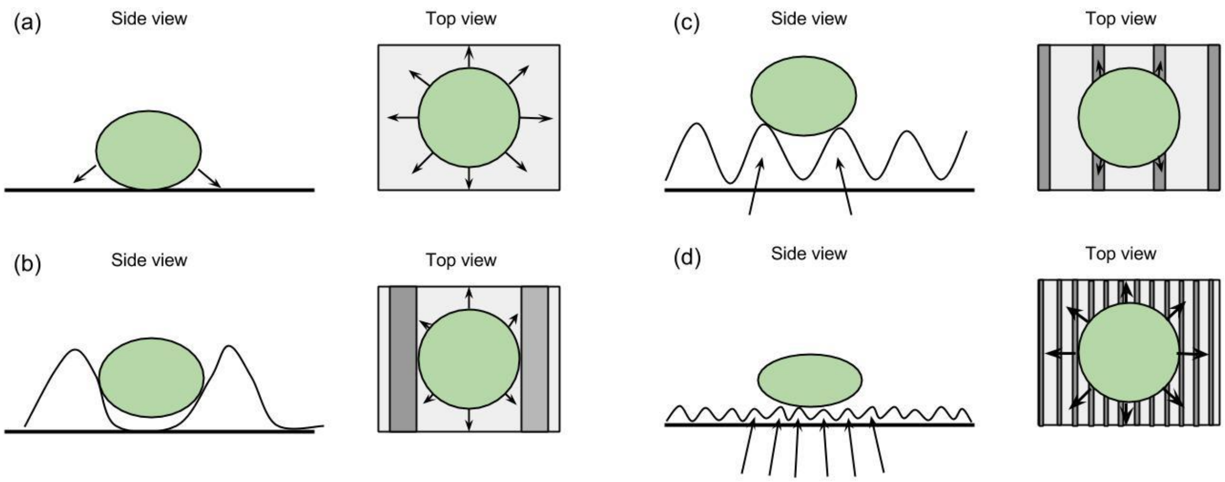

Figure 8 By shrinking the ripples on a surface, the numbers of attachment points shrinks in relation to a one sized diatom. a) The attachment points on a planar surface, b) To big ripples offers refuge, c) unattractive settling conditions since only two attachment points are offered, d) too many and too small ripples get the reverse effect and creates attractive attachment conditions. The green circle represents a marine organism that is roughly 5 microns across for scale

Another fouling theory that has been developed together with the topographically engineered surface *Sharklet AF (see below)*, is called the *nanoforce gradient*, see Figure 9. This theory predicts a small force gradient, created by the surface topography, to induce stress on settling organisms. Carefully designed and engineered force gradients may be used as an effective tool and predictive model for settlement behavior. A model that would make way for the design of unique nontoxic, antifouling surfaces to be used for marine applications (as well as for biomedical applications). The hypothesis states that nanoforce gradients, caused by variations in topographical features, will induce stress gradients within the lateral plane of the plasma membrane of a settling cell or microorganism during initial contact. The Sharklet pattern, also illustrated in Figure 11, is designed with different sized ridges that make up a diamond shape pattern inspired by sharks. This stress gradient and nonequilibrium state will function by disrupting the normal cell function, and in this way influencing specifically the settlement process. With a surface topography creating a stress gradient on the settling organism, it needs to compensate, thus spend energy, in order to adjust its contact area on each feature, such that the stresses are equal. If, however, the organism find that the energy necessary to settle may be to thermodynamically unfavorable, it will leave and probe another area to settle. The appropriate dimensions of structures that cause as much stress as possible are controlled by the bending moment, or stiffness, of the topographical feature that an organism is in contact with. The geometric dimensions including width, length and height of the topographical feature, as well as the modulus of the base material, define its stiffness. If you embed variations in the topographically features, like done in Sharklet, an effective force gradient between neighboring features will be developed. A cell, trying to settle on two different sized topographical features, will experience a stress. The stress induced varies depending on the difference between the structures but is hopefully enough to make the organism chose another place to settle (43).

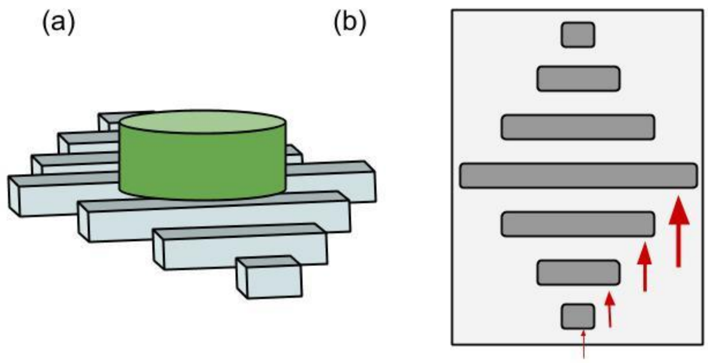

Figure 9 A nanoforce gradient depends on the chosen geometries. The red arrows in b) indicates the force difference required to cause a 10% end deflection of the micro-structured topography. This is felt by the settling organism in a) which leaves the surface if the induced stress is too great. The green cylinder is roughly 10 microns across for scale.

Topographies from both pilot whales and shark skin have been characterized. Their antifouling abilities have been identified to, to some extent, depend on the microstructures of their skin. The structures could be described as well-defined ridges scaling from 1 to 300 microns with multiple length scales (i.e. structural hierarchy), meaning the small microstructures make up even bigger structures (40). Another family, the Mollusks and some of their shells, have a topographical surface that reminds about the shark surface. Although, the skin of the Pilot whale, *Globicephala melas*, offers a combination of solutions which will be explained below.

Mechanical

If marine animals haven't had the luck to develop a surface texture that takes care of the problem on its own, they need to look for assistance. Grooming is a common AF mechanism found throughout nature. Grooming involves specialized structures to either pick or sweep an animal's surface clean from fouling organisms. One example is ciliary cleaning, that many organisms use in conjunction with mucus to keep surfaces clean; much like the tiny hairs in the respiratory tract of humans that pushes unwanted particles out of the way by wiggling back and forth (44). Snails use mutualistic grazing within a population, they clean each other's shells, and crayfish take help from branchiobdellid annelids, a type of worm, to stay clean from epibionts in the gill chamber, two examples of symbiosis in nature. Just like humans some marine animals use shedding or molting to renew their outer layers. Crustaceans, stone fish and algal all molt their outer layer, either in patches or all in one go. This allows them to lose all their fouling. Additionally, many organisms use mucus to separate them from the environment. Just like a barrier separating the animals from the fouling entity, and hence they have difficulties to adhere and sloughs off easily (40).

Behavioral

This category is the hardest for a marine vessel to mimic. Since it evolves the direct or indirect active avoidance of fouling organisms. Burrowing yourself down in the sediment, jumping up through the air, swim between fresh and salt water or into areas with different oxygen content are some examples marine animals use to stay fouling free. This will remove all organisms that are less tolerant than their host (40).

Combination

Most organisms that are studied use a variety of anti-fouling mechanisms. It is most likely that marine animals have more than one way to fight the problem of marine fouling. Below we will describe some biological systems found in nature that combines different techniques to prevent fouling.

The **Pilot whale,** *Globicephala melas*, has been extensively researched in order to try to understand the self-cleaning abilities of its skin. The so-called perfectly smooth surface of the pilot whale actually displays small tips arising from the average smooth background. Underneath you will find nanoridges (approximately *100 nm* deep) and nanopores (diameter approximately *0.1* and $1.2\ \mu m^2$), smaller than most marine fouling organisms. These micro- and nanosized structures makes it harder for organisms to adhere i.e. creating a smaller contact surface. Foulers that attach are limited to the margins of the pores or the tips of the nanoridges. Beyond the small structures one will find heavy enzymatic (*keratinolytic*) digestion process that kills everything that tries to settle. The structured skin, in combination with the whale's behavior, makes it hard for organisms to settle. During jumping, attached particles not protected from air bubbles within microniches in the skin get in contact with the air-liquid interfaces or high-speed water flow and falls off as a result of these detaching forces (45).

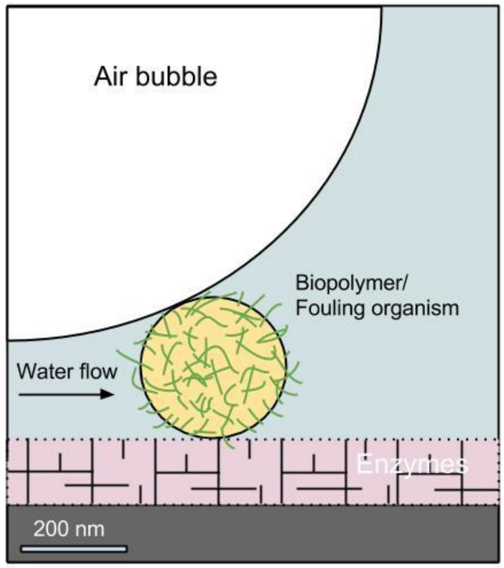

Figure 10 Having a surface offering minimal attachment point and a behavior consisting of jumping, the Pilot whale can stay fouling free.

Coral in general uses antibacterial mucus, slough mucus and surface layers secrete secondary metabolites to keep their surface clean. They also select specific microbial colonists to care for, that in return protect them from other microbes (40).

The **dogfish egg-case**, *Scyliorhinus canicula,* has been of interest for some studies. It doesn't prevent all fouling, but avoid some. It has a microstructured surface. It is also proposed to possessing a novel class of natural chemical defense. It has been proposed that iron and manganese, on its surface, cause oxygen free radicals produced through the Fenton reaction (46).

Research suggest that a combined mechanical and chemical defense strategy is used by some **echinoderms** (i.e. starfish). The conclusion, after also trying out extracts from the outside of its body for AF properties, is that the group *Echinoderm* needs more research in order to learn more about their combined physical, mechanical and chemical defenses (46). Some groom, slough, excrete anti-adhesive mucus, have chemical antifoulants and some have been suggested to use a strong negatively charged cuticle to prevent surface colonization.

Another family, which is said to both groom, shed their shells and use behavioral mechanisms is the **Crustaceans**. Burrowing in the sand or moving among habitats in the ocean crustaceans ensures to keep a fouling free surface (40).

Algae in general might be a hazardous soft macrofouling organism for man-made structures, but in turn, still an organism that needs to control fouling on its own body. In order to prevent fouling, they use chemical metabolites, shed their outer layers and remove settled epibionts by flexing beyond what the foulants can withstand (40).

One method that most **species of fish** employ is the creation of a slippery surface, by producing slime, which makes it impossible for organisms to settle. If the organisms do settle, the slime layer is continuously renewed and they will fall off eventually (47). The mucus found on dolphins, fish and corals for instance, have also been identified to contain chemicals having antifouling properties. Some that dissolves glue, some that prevent attachment or act as antimicrobial toxins (40).

Solutions inspired by Nature

Chemicals

The quest for finding the optimal solution, using the same chemical defenses as nature, has led to a list of different active ingredients. Many of them work great in a laboratory environment but have issues in applications. The issues with picking a chemical used by marine organisms as a natural AF system are many. It should be easy to synthesize in big quantities, not too expensive and not too poisonous for the ecosystem, nor bioaccumulative. However, the hardest problem seems to be mixing it with paints. As mentioned previously, a biocide embedded in a paint should be released in an even and continuous pace in order to prevent growth for a long time. This requires a molecule with special properties, properties that are very hard to find in nature (47). Since the ban of TBT, the environmental awareness has increased. As a result, it takes both a lot of time and resources, to introduce and get approval of a new biocide. To take a chemical substance from identification to commercialization, can cost millions of euros and take over 10 years to get approved (40). To date, thousands of active natural products have been identified, but the number making it to the market is not as great (40).

SeaNine 211, is a booster biocide, meaning it is used as an additional biocide in coatings. Sea Nine 211 is used in combination with copper coatings to tackle fouling plants. It has a great performance record both in lab- and field studies. It degrades quickly in water and sediment and has low environmental toxicity. SeaNine is based on the natural product *isothiazolone*, which was in the 1980s isolated from the soft coral *Eunicea* (40).

Econea, yet another booster biocide that sometimes is combined with the SeaNine 211 for its specificity against animal fouling. It is a halogenated pyrrol and is the active ingredient in copper-free AF paint. Halogenated pyrrols are often found as secondary metabolites in microorganisms like bacteria, meaning it is already a well-used AF-chemical found in nature (40).

Capsaicin is a natural occurring substance, not found in any marine organism, but in Spanish pepper. It is this substance that causes the burning sensation on your tongue when you eat it. Many organisms, just like humans, tend to avoid capsaicin and capsaicin treated surfaces. Capsaicin has found its way to the market on a small scale (47).

Mechanical

One tried out method, that could be called bioinspired, is a surface renewal technique where polymers in contact with water hydrolyze, leaving a clean surface behind, just like the shedding of *Crustaceans*. This is called self-polishing copolymer, SPC, and is a technique described later on. To date, the SPC remains ineffective if not combined with biocides.

Today, when a ship is fouled to such extent that it needs to be taken care of, you might look at either cleaning or grooming techniques in order to extend the dry dock interval. The first is said to be rougher to the hull, to tackle macrofouling, whereas the word grooming refers to a gentler cleaning, often with soft brushes. The best way is surely a preventive technique, but if you get to this point, you don’t have much of a choice. Cleaning is often carried out with big and bulky equipment in connection with a harbor. Many cleaning techniques are today banned in harbors since they often risk the spreading of non-indigenous species (40) and cause the immediate release and increased release speed of biocides if used on hulls painted with biocidal coatings (48). Cleaning is said to be reactive and has been shown to speed the rate of recolonization (40).

One variety of cleaning is via **hydrodynamic cavitation**, a method you carry out underwater. You shoot a high impact jet of water on a surface, air bubbles are created and by collapsing, the air bubbles create a shockwave which makes fouling organisms come off. The method is said to be effective against all types of foulants. The downside is that it might damage the coating and it requires personnel to perform the service (49). The same is said about mechanical brush cleaning devices, two of them called **SCAMP** and **Mini-Pamper** (40). A device that starts to appear in harbors for leisure boats is the so-called ‘**Boat Washer**’; a brush station installed in the harbor that is able to brush boats hulls up to the length of 20 meters. It is supposed to only take 15 minutes to clean a vessel that is 6-8 meters long. The initial cost for the brush station is quite high, roughly 80.000 euros. It is not stated how much of the biofilm (50) is removed but the U.S Company, **Stark Boatwasher**, provides test results showing that the top speed rose with 14% and fuel consumption sank with 10% after use (51). The problem with invasive species is not as severe for leisure boats since they travel in a limited area.

The next generation of mechanical cleaning is said to mimic natural grooming. That is the idea behind the **HullBUG** (Hull Bioinspired Underwater Grooming). It is an autonomous robot developed by **SeaRobotics** and funded by ONR (Office of Naval Research). The robot is supposed to tackle the biofilm that gathers on a ship hull while in port. It is equipped with small gentle wipes and brushes and with a sensor in the nose to detect biofilms (52). Mechanical antifouling solutions are a good, but imperfect method to tackle fouling. It is best when combined with another antifouling method like a fouling releasing surface.

Another upcoming technique is **Hull Surface Treatment** (HST). That only uses heated sea water that is sprayed on the hull. The tool is moved up and down along the hull by an operator. The ship is still in the water. All the organisms die instantly by thermal shock and are flushed away later on with hydraulic forces once the vessel leaves port. With these conditions HST can safely be used in port, without risking to spread invasive specious (53).

Physical

Sharklet

A technology that depends on topographic structures is the film named Sharklet. A solution inspired by the only slow moving marine animal that doesn't foul - the shark. Sharklet has ridge-like structures that mimics the dermal denticles of the shark. On their body you will find them patterned in a diamond like pattern with tiny riblets. The ribs' width-to-height ratios correspond to Dr. Antony Brennan's (the inventor of the Sharklet pattern) mathematical model for roughness. The pattern discourages microorganisms from settling because it requires too much energy for bacteria to colonize. The consequence is that organisms find elsewhere to grow or just simply dies from inability to signal to other bacteria. A first test of the microstructured surface reduced green algal settlement by 85 percent, compared to a smooth surface (54). Today, the company *Sharklet technologies* that license the product, have their focus on medical device and healthcare markets. The research to apply the technology as an antifouling technique remains at the University of Florida where it was originally invented. *Sharklet technologies* predicts the need for extensive capital before it will be realized (55).

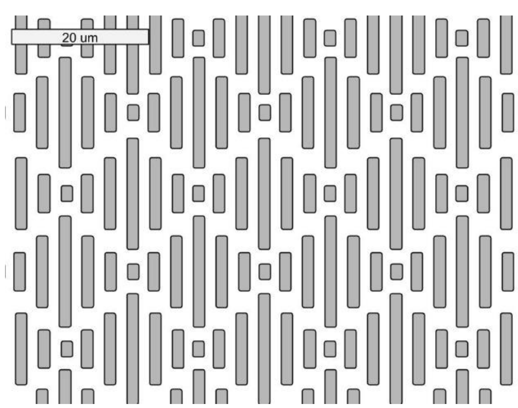

Figure 11 An illustration of the Sharklet pattern. The scale bar is 20 microns.

SealCoat

SealCoat is a coating said to mimic the fur of seals. Seals are known to be fouling free. SealCoat has a fiber-like structure that overlap one another. According to the inventive company it tends to remove all settling organisms and their product will keep your hull fouling free for up to five years (something not backed up by scientific results) (56). It should be reminded that seals do not only rely on their fur to keep themselves fouling free, they also tend to groom and stay out of the water for hours each day (40).

Antifouling Today

In this section, the different methods to prevent and treat marine fouling will be presented both the main ones and the ones less well known. The four main technologies used today are **Self-Polishing Copolymers** (SPC), **Fouling Release** coatings (FR), **hard paints** and **Controlled Depletion Polymer** (CDP). The design of antifouling coatings and materials can be based on three different approaches.

(1) Prevention **-** by preventing fouling organism to attach to the surfaces
(2) Release **-** by releasing the attached fouling organisms
(3) Killing or weakening **-** by using toxic substances or altering the environment in an unfavorable way for the fouling organisms.

Before the methods mentioned above will be described, a short simplified explanation of the difference between antifouling (AF) and fouling release coatings (FR) will be made. AF and FR represent the two general solutions (18). AF corresponds to methods that *prevent the microorganisms from settle* on the surface, often with the release of biocides. The FR paint on the other hand focus on *making the attachment as weak as possible*. This allows the attached microorganisms to be detached easily by the shear force of the moving water or by soft cleaning (a cleaning method later described).

Contact leaching coatings

Known for its good mechanical strength this type of paint is also known as **hard paints**. Using binders that are insoluble in water with a high molecular weight as acrylics, vinyl, epoxy or chlorinated rubber polymers gives the paint its hard surface (57). Biocides are also incorporated with the binders. Important to notice is that the biocides are soluble in water. Since only the biocides are soluble in water it is released from the paint creating a structure with channels where the biocides used to sit. The water spreads through these channels, or pores, dissolving the biocides on its way. When the water flows further and further into the structure the amount of released biocides decrease. This makes contact leaching coatings only efficient up to 24 months.

Hard paints without biocides

Hard paints differ from contact leaching coatings primarily by not containing any biocides. Instead they rely on their hard surface for protection against fouling organisms. The hardness comes from glass flakes contained in the paint (58). The principle behind this paint is that the hardness makes it difficult for organisms to make a good attachment to the surface and thereby they easily falls off. The AF properties of this type of paints are not as good as for example **SPC** and surfaces treated with hard paints without biocides, has to be cleaned more often. According to the shipping company Wallenius Lines website (58), the main problem with this is the need of protecting the environment where the cleaning is done from foreign species. However, hard paints are ideal for vessels traveling in icy environments where they naturally get cleaned by the ice. These types of paints need very little maintenance and some manufacturers even say that a full repaint is never needed (58).

CDP

Controlled Depletion Polymer paints were released as the first tin-free paint for antifouling (58) and it was developed to prevent the loss of protection over time, i.e. to reduce the dissolution of itself in water. To manage this, rosin was used, having the ability to slowly dissolve in water. However, the use of rosin also presents difficulties primarily due to its sensitiveness to oxidation, which in turn required a ship's time on land after painting to be kept at minimum (2). When the rosin is in contact with water the carboxyl groups in the rosin react with sodium and potassium ions that lead it to dissolve (2). To get a desired dissolution rate and to change the brittle nature of rosin, it is often blended with copolymers and plasticisers. The biocides, mixed in the paint, will dissolve faster than rosin due to diffusion, leaving behind a matrix-like structure. This is called a leached layer, illustrated in Figure 12. The leached layers easily build up over time under static conditions, something that results in reduced antifouling properties at low speeds (2). When the rosin level is above a certain level, **CDP** paints also show the property of releasing exponentially more paint with increased velocity. These sets of properties makes **CDP** release the least amount of biocides when it is needed the most, and that is when the vessel sits idle. Due to the roughness created by the leached layer, the fuel consumption will increase over time (58). **CDP** is copper based and it often contains booster biocides being stronger and more toxic compared to other AF-paints (58). At the same time, **CDP** has also the largest leakage of biocides. The leakage is often considered initial and decreases over time because of the leached layer, which also has a negative effect on recoatability. **CDP** are best suited for vessels that have a short docking cycle or travel in low fouling areas (59).

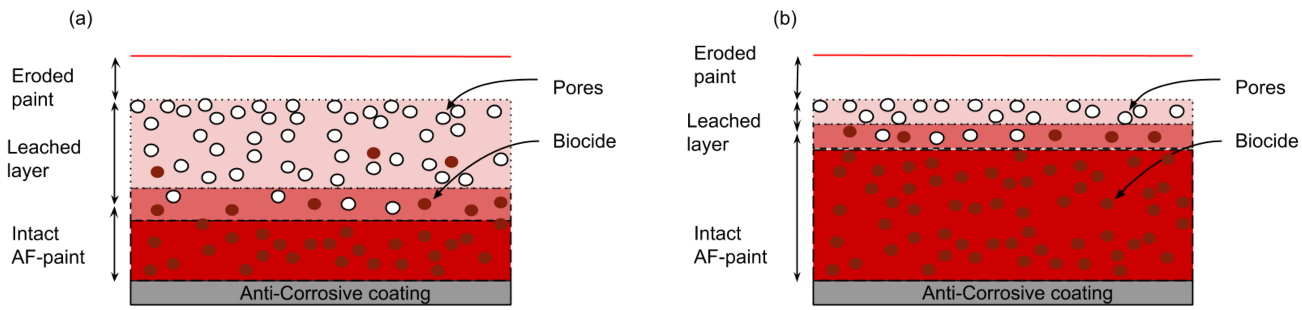

Figure 12 An illustration of two biocide-release paints after contact with sea water for some time. (a) Controlled Depletion Polymer where the thick leached layer can be visualized. (b) Self-Polishing Copolymers, has a thin leached layer that is easily washed off.

SPC

As the name implies, **Self-Polishing Copolymers**, polishes their surface slowly, continuously releasing the outermost layer of paint into the sea. **SPC** paints are based on acrylic copolymers that hydrolyze in seawater (60). **SPC** also contain biocides and by controlling the erosion rate of the binder (copolymers) the release rate of the biocide is controlled. In turn, the erosion rate of the binders are affected by their polymerization (molecular weight) and hydrophilic properties (61). In contact with water the soluble biocides, or pigments, dissolve. The copolymers are hydrophobic and prevent the water from penetrating the paint, slowly dissolving because of the ester group in the copolymer becomes hydrolytically unstable under alkaline conditions (57). When the copolymers are hydrolyzed they form an acid polymer, soluble in water (59). This creates a slow and controlled hydrolysis of the outermost layer from the surface, at the same time as the dissolving process causes the release of biocides. As the process proceeds, it leaves a thin leached layer behind, visualized in Figure 12, consisting of brittle polymers that are easily washed off by the seawater together with the fouling organism. **SPC** paints are designed to typically have a polishing rate of *5-20* μm a year, which allows it to last for up to 5 years. **SPC** paints are the dominating AF-paint and make up 80% of the marine antifouling paint market (61). **SPC** paint is more efficient than **CDP** and can be tailor-made for vessels, due to the very accurate control of release (59).

Hybrid

Hybrid AF paint, also called Self-Polishing Antifouling, (59) combine the properties of **SPC** and **CDP** technology to increase the efficiency of the paint. This is done by combining **SPC** acrylic polymers and rosin. A paint is created that relies on both hydrolysis and hydration to release biocides. By combining the two, the **hybrid paint** gets the desired *surface tolerance* and *volume to solid* from the **CDP** with the advantages of **Self-Polishing**, a well-controlled biocide release rate and a thin, leached layer. This gives **hybrid paints** both the performance and price in the range between the **SPC** and **CDP.** It is especially suitable for vessels traveling in tropical and semi-tropical waters for its good antifouling properties (59).

Fouling release coatings

The most common materials used for fouling release coating (**FR**) are poly(dimethylsiloxane) elastomers, also called PDMSe, and fluoropolymers (18, 57). The releasing properties are related to surface hydrophobicity, low surface energy, surface roughness, elastic modulus and thickness of the coating (18). According to Irwin et al. (62) the minimum of adhesion relates to the lowest value of elastic modulus but not the lowest surface energy. The mechanism of fluoropolymers and silicones to prevent fouling differs. Fluoropolymers create a hard, glassy and nonporous coating with a lower surface energy to which the biofoulers adhere weakly. This is due to the high resistance of the surface to molecular internal diffusion and rearrangement which gives a sharp and well-defined interface between the biofoulers and the substrate (57). This interface is easily broken by in-plane or out-of-plane shear stress. The critical stress needed for fluoropolymers, compared to silicon-based coatings, are generally greater due to a higher bulk elastic modulus value. Silicon-based coatings, as mentioned earlier, generally have a low (lower than fluoropolymers) elastic modulus but a higher surface energy. The higher surface energy allows the foulers to bind more strongly to the surface while the lower elastic modulus, lowers the energy required to release foulers. This is because the lower elastic modulus allows the silicon surface to deform with force applied and cause the foulers to release (57). The thickness of the coating also affects its releasing properties. A thick coating results in better releasing properties than a thin coating (62). Ideally, the **FR** coating provides a surface that is so slippery, that the fouling organisms can’t attach (62).

Enzyme based coatings

The use of enzymes for antifouling coatings is an area that have gained increased interest the last years in antifouling research. Enzymes can be viewed as a type of biocide and are included in regulations of biocides within the EU (57). Found everywhere in nature, enzymes are catalyticall proteins that have the ability to degrade fouling organisms. The enzymes are bioadhesive or produce biocides of their own. The different modes of enzymes can, according to Olsen et al. (63), be divided into direct and indirect. *Direct* corresponds to enzymes that actively interfere with fouling organisms while *indirect* corresponds to enzymes that provide the biocides from its surroundings. *Indirect* can obtain the biocides thanks to enzyme converting compounds from seawater into *direct* antifouling compounds (64). The *direct* enzymes work in the same way as normal biocides. The released enzyme targets the fouling organism and decreases the amount of fouling. This can be done by either targeting its bioadhesion or by having toxic effects on the foulers, affecting the viability of the fouling organisms. The requirements of enzymes to be used in novel antifouling solutions can be described with the four following steps:

1. Stay active when mixed with coating compounds.
2. Not interfere with coating performance.
3. Show antifouling properties for a broad-spectra of fouling organisms.
4. Stability in long-term both when dry and under submersion.

Biocides

A selection of biocides and booster biocides will be described in short terms. The selection of booster biocides is based on the same selection as the European Environment Agency, EEA, did in its report: *Late lessons from early warnings: Science, precaution, innovation* (65). Copper is the main antifouling biocide used today and degrades to Cu^{+} and Cu^{2+} ions in seawater where Cu^{2+} is the more stable one (60). It exhibits antifouling properties against barnacles, tube worms and most fouling algal. Copper is perceived as toxic by reducing the organisms' osmoregulation and ion regulation in the gill (64).

Booster biocides

Booster biocides were developed due to the urge to replace TBT and because of the fact that some algal are tolerant to copper (2). By definition, booster biocides are an added biocide to an already biocidal paint.

Chlorothalonil, used as a pesticide in agriculture and urban environments. In marine antifouling purposes, it is used as a booster biocide against fungi and fungal spores. It has been reported to be bioaccumulative in fish (64).

Dichlofluanid, used as an herbicide on crops, show low toxicity compared to most biocides (64).

DCOIT (also known as *SeaNine 211*, mentioned above) is rapidly chemically and biologically degradable, forming compounds that are up to 100 000 times less toxic than the original substance, in both anaerobic and aerobic conditions (64). **SeaNine** is toxic to a wide range of non-target aquatic organisms (i.e. organisms it is not supposed to kill), but its effect is reduced due to the rapid degradation (66).

Diuron, used as pesticides in a wide range of areas e.g. fruit farms, vegetable farms and drain channels. It is used in antifouling paints to protect against growth from algal (67) and is reported to be very toxic for the reproduction of green freshwater algal, in addition to reducing the chlorophyll levels in planktonic and periphytic microalgae (64). **Diuron** is derived from urea (68). It is according to Hironobu et al. (69) one of the most permanent contaminants in marinas and has a low solubility in water (68).

Irgarol is used as a booster biocide and reduce fouling by inhibiting electron transport in photosystems (64) and is effective against fresh and seawater algal (36). **Irgarol** degrades slowly in water and is often used in combination with copper (70). A decrease in growth, inhibition in cell number and a decrease in photosynthesis have been seen in organisms due to **Irgarol**.

TMCS pyridine, newly introduced as an antifouling booster biocide. **TCMS** has earlier been used in leather and textile industries (64). Preliminary studies of the environmental effect of **TCMS** showed similarities with TBT, but further research is required (68).

Zinc pyrithione, used today as algaecide, bactericide and fungicide. For aquatic plants and mammals **zinc pyrithione** is highly toxic but according to Francisco et al (64) it is thought of as environmentally neutral since it easily photodegrades into less toxic compounds.

Zineb. Similar to many other biocides **Zineb** is used in agriculture and industrial applications. Some of the registered areas of use are on fruits, vegetables and field crops. **Zineb** is toxic to bacteria.

Selektope, or Medetomidine (71) is the Swedish based company i-tech's novel biocide. It is selective, mostly against cyprids (barnacle larva). It can be used in a very low concentration in marine paint (0.1%), and still be effective, due to its selectivity. The cyprids are reported to have a low tendency to settle when they encounter a hull with **Selektope,** being due to that **Selektope** inhibits their settling mechanism resulting in that the foulers try to find a new place to settle. Once the organism leave the surface treated with **Selektope** they get back to normal behavior, i.e. **Selektope** it is reversible and localized to only the surface.

The half-life for the booster biocides is presented and can be easily compared in Table 1. Half-time is the time it takes for a substance to fall to half of its original concentration in water (72).

Irgarol 1051	100 days
Dichlofluanid	10 hours
Chlorothalonil	1.8 days
Sea-Nine211	< 24 hours
Zinc pyrithione	< 24 hours
TCMTB	31 days
Zineb	96 hours
Diuron	> 42 days
Selektope	Unknown

Table 1 The half-life for the booster biocides mentioned above (65).

Booster biocides and environmental impacts

Biocides are, according to the European Environmental Agency, EEA, undeniable and necessarily toxic in their nature (65). The damaging effect to the aquatic environment and the contamination of coastal areas are documented for multiple areas with the result of a ban of some booster biocides (65). High levels of **Irgarol** has been observed in coastal areas in Europe, Bermuda, U.S., Japan, Singapore and Australia (65). Especially alerting is that high levels of **Irgarol** are found around coastal areas of Australia where it has never been used in the shipping industry. Toxic effects due to boosters biocides with herbicidal properties are worrying, according to the EEA. Many aquatic plants seem to be especially vulnerable to these types of biocides.

The regulations for introducing novel biocides on the market requires extensive investigations to be certain of its impact on the environment to prevent the legalization of new substances that have a disproportionate risk of damaging the oceans. It is described as a process being so demanding that the more environmentally friendly biocides have to wait many years before they will hit market, according to Lena Mårtensson at I-tech (48).

The obvious solution would be to stop using biocides. However, this is something that can result in an even greater harm to the environment. This is due to two main reasons.

1. **Antifouling solutions reduce fuel consumption.** The exhaust from trading vessels is some of the world’s worst exhaust emissions per ton fuel. This, in combination with that trading vessels can consume more than 150 tons of fuel per day, makes fuel savings utterly crucial.

2. **Antifouling solutions prevent the spreading of invasive species.** The spreading of invasive species due to fouling is an increasing problem and has resulted in the banning of cleaning methods used in harbors in many countries (48). Invasive species are spreading and competing with native species putting sensitive biological systems at risk.

TBT

Introduced in 1974, TBT (tributyltin) revolutionized the antifouling market. Its performance resulted in major reductions in fuel consumption and longer docking intervals compare to other alternative coatings (63). TBT coatings were the first self-polishing coatings (SPC). The antifouling properties were so effective that the development of new antifouling alternatives stalled. When introduced it was thought less toxic than the alternatives, such as DDT and arsenic (73). Today we know that TBT had very severe effects on the aquatic environment that in 2008 led to a worldwide ban of the substance. Studies have found that TBT, for instance, disrupts the endocrine system of marine shellfish, resulting in the development of male sex organs in female marine snails (74). Even in very low concentrations TBT shows toxic effects.

Experimental Methods

Experimental methods include methods that have been researched but not yet commercialized, or, are very new to the market without any reliable track record.

Antibacterial materials

By using so-called antibacterial material on surfaces, the surfaces will obtain biocidal effect without releasing biocides. An example is when quaternary ammonium salts (QAS), a substance with natural antibacterial properties, is covalently bond to a surface. The most well-quoted theory about why QAS show antibacterial properties suggest that long cationic polymers penetrate cells and thereby disrupt the membrane, causing it to break. An alternative hypothesis postulates that the highly charged QAS surface will cause an ion exchange between the surface and the cell membrane, causing the loss of structurally critical mobile cations within the membrane that in turn is fatal to its integrity (69). The charge density and chain length of the QAS are correlated to the bacterial effect (61). Using antibacterial surfaces, rather than releasing biocides, reduce the likelihood of generating resistance to the active agent. Polymeric antimicrobial materials are reported to have been successfully bond onto polymer, paper and metal (69). No known examples of antifouling implementations of antibacterial materials, available today, are known to the author, but the area show promising results for future implementations with limited or none biocidal release.

Surfaces with Dynamic Topography for Active Control of biofouling

A common way for marine organisms to clean their surface is via the small movement of an active surface. Examples of active surfaces are algal that stretches or bend from the movement of water and ciliary cleaning. A surface made to mimic cilia has successfully been replicated in the laboratory but struggles with a complicated fabrication process, development of practical actuation schemes and fragile structures that might break under the harsh environment from the ocean. In the article *Surfaces with dynamic topography for active control of biofouling* by Shivapoja et al. (75), describes a surface that offers dynamic change of surface area and topology as a response to external stimuli, illustrated in Figure 13. The surface is fabricated from already available materials. It can also be fabricated to cover large areas and can be actuated easily through electrical or pneumatic stimuli. In the article Shivapoja et al. tries to stretch an elastomer to such an extent that both micro- and macrofouling releases from the surface. The first experiment was a sandwich construction with aluminum foil covered with a silicone elastomer on top of an isolated surface. By applying DC voltage, an electric field was created in the elastomer in which, after reaching a critical value, the elastomer got unstable, deforming into a pattern of craters. *95 %* of the biofilm was detached after a *10-minute* period with *200 on-off cycles*. They continued to stretch an elastomer with mechanical force to see whether their hypothesis was correct and that the detachment of the biofilm was not caused by the electric field. Another approach was to fabricate a pneumatic network covered with an elastomer. By changing the air pressure in the network, they caused a strain in the material and the biofilm detached. For example, an air pressure of *3 kPa* induced *23 %* surface strain, resulted in an almost *100 %* detachment of the biofilm. However, the article state that this method is suited as a complement to enhance other antifouling solutions e.g. micro- and nanotopography (75).

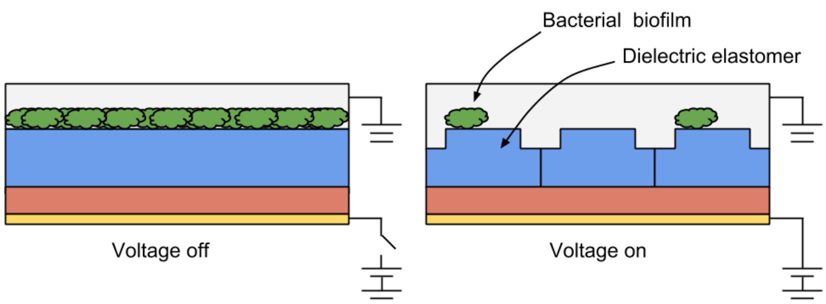

Figure 13 By applying a voltage which induces an electric field a deformation of a fouled elastomer surface can be achieved with 95% of a bacterial biofilm successfully detached from stretching the dielectric elastomers.

Ultra sound

On the market for leisure boats, antifouling solutions using ultrasonic sound can be found. Some examples are *Sonic Shield*, *Ultrasonic Antifouling* and *Sonihull*. The principle behind these is to use an ultrasonic transconductor, a device that sends out ultrasound. The transconductor is placed on the inside of a ship's hull, acting as a conductor for the sound waves. *Sonihull* claim on their website that their technique produce a pattern of alternating positive and negative pressure (76). The alternating pressure creates microscopic bubbles during periods of negative pressure that is imploded during the periods of positive pressure (this is a phenomenon called cavitation). This implosion creates a micro-jet water motion that helps to clean the hull and kill single cell organisms, according to *Sonihull*. Ultrasound has also been investigated in scientific studies and results have shown that frequencies on the order of tens of *kHz* efficiently kill barnacle larvae (37). Ultrasonic sound has also been used to pulverize the nauplii stages of barnacles due to cavitation (77) and cyprids exposed to ultrasound showed lower settlement rate and higher mortality (37). The decreased settlement and increased mortality is probably because of the physical damage done by the ultrasound. However, the ultrasound doesn't show any effect on cyprids that have gone through metamorphose (37).

Electrical field

An interesting approach as an antifouling solution is the use of strong electric fields investigated by Rodolfo E et al. (78, 79). The articles investigate the effect of localized, low-voltage pulsed electric fields on a biofilm of *Pseudomonas aeruginosa* bacteria and the settlement of barnacle *Amphibalanus amphitrite* cyprid. The use of electric field resulted in a major decrease in the settled bacteria and cyprids. By using small structures, low-voltage produces a high-strength electric field. Tests showed a decrease of *Pseudomonas aeruginosa* with up to 50 % on the area covered by electrodes (78). The mechanism behind the reduced biofouling was never presented by Rodolfo E et al. In vitro studies for dental research has also shown that electrical currents (DC) can stimulate detachment of bacteria (74).

Carbon nanotubes

A new approach for antifouling solutions is provided by a company called **Nanocyl**. They have developed a solution called **Biocyl,** which uses multi-walled carbon nanotubes (MWCNTs) in a liquid dispersion based on silicone resins. This is a type of fouling release additive being employed in silicon-based blends. **Biocyl** has showed efficiency in blends with concentrations as low as 10 % (80). According to Nanocyl, barnacles will be removed at speeds as low as 4 knots. A Biocyl based top coating has proven equivalent with the best antifouling solutions available today (80). The technique works due to the fact that the carbon nanotubes, when the coating is submerged, tend to rise and stick out from the surface (for an unknown reason to the authors) which creates more slippery conditions for adhering organisms, see Figure 14. The slippery surface is due to the carbon nanotubes only allow the fouling organism to lightly adhere, according to Daniel Boundel at Nanocyl (81).

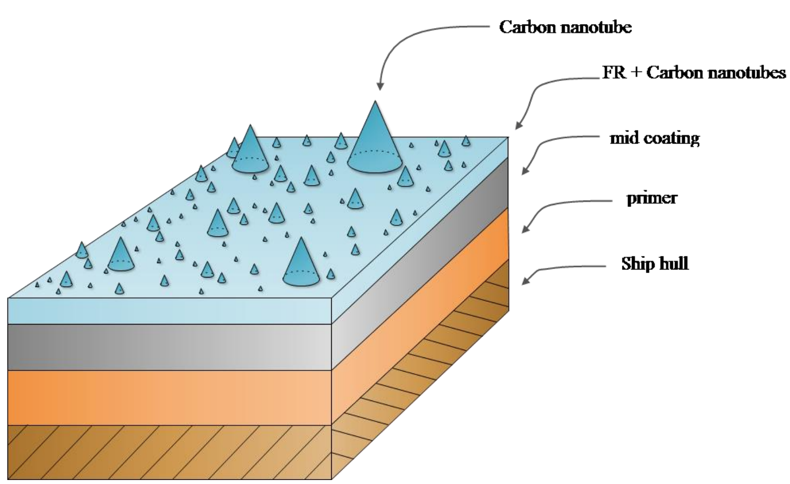

Figure 14 When Biocyl, a coating containing carbon nanotubes, is submerged in water the carbon nanotubes tend to rise and create a slippery surface for fouling organisms.

Analysis

In order to evaluate and compare the techniques used on the market today a SWOT analysis is done in combination with a GAP-analysis. The purpose of the GAP-analysis is to emphasize the gap that novel solutions have to fulfill in order to meet future demands.

SWOT

The antifouling solutions selected for the SWOT analysis (*Strength*, *Weakness*, O*pportunities* and *Threats*) are based on the techniques earlier mentioned in the report. In addition to the main solutions used today, a few more novel and unusual antifouling solutions are selected due to the author's own interest. The SWOT analysis is presented on the following page.

Antifouling Technology (Description)	**Strengths**	**Weaknesses**	**Opportunities**	**Threats**
HullBUG (Grooming device)	- The boat can stay in water during cleaning - The cleaning process can be done anywhere - Can be used on most existing coatings - Environmentally friendly (as long as the cleaning don't release foreign species) - Reduced fuel consumption if done often, due to reduced fouling/ drag. - Treatment of fouling in an early stage possible - Can use several units at the same time/ boat, resulting in quick cleaning.	- The vessel has to remain in port during the cleaning - High release of biocides if the vessel has a biocide release based hull antifouling paint due to the cleaning - Only supplementary to a antifouling coating - Only for microfouling - May harm sensitive hulls	- Laws/ regulation of biocides - Environmental concerns are increasing, more aware costumers - May be applied worldwide - Possible to upscale	- Release of foreign spices during the cleaning process - Dependent of operator/ unit - Regulations on cleaning due to possible release of foreign spices
Boat washer (Cleaning device)	- The cleaning process is done when the vessel stays in water - Quick - Cheap - Can be used on existing coatings - Remove most micro- and macrofouling - Could be installed in all leisure boat harbors - Environmentally friendly - Cost saving due to removal of fouling organism that may cause increased drag	- Stationary - Only supplementary to the boats antifouling protection - High initial cost to purchase - May harm sensitive hulls - The boat size is limited to 20 meters - Needs an operator - High release of biocides if the vessel has a biocidal coating - The boat needs to remain in the dock during the cleaning	- Laws/ regulation of biocides, - Environmental concerns are increasing, more aware costumers - May be applied world wide - Possible to upscale	- Release of foreign species during the cleaning process - Dependent of operator/ unit - Regulations on cleaning due to possible release of foreign spices
Active control with dynamic topography (Experimental coating)	- Very efficiently according to initial tests - Can be complementary, can either be used together with present techniques or in itself - Produced with already existing materials - Easily up scaled - Biocide free, environmentally friendly - Could be applied with known applying methods	- Only release, don't tackle growth - Needs DC-current or pneumatics - In research state - Needs to be applied in dry docks	- Laws and regulation on biocides might become more strict - Environmental concerns increase (more aware costumers)	- Release of foreign species during the release process - May not see commercialization - Need further research

Antifouling Technology (Description)	**Strengths**	**Weakness**	**Opportunities**	**Threats**
Hard paints without biocides (Coating)	- Long lifecycle - Low maintenance - Mechanically hard - Limited fouling when used in the right environment (ice) - Used today - Biocide free - Cheap	- Poor antifouling properties - Requires more cleaning - Requires specific condition to not experience extensive fouling - Limited use - Needs to be applied in dry docks	- Laws and regulation on biocides might become more strict - Increasing demands on hard paint in combination with regular cleaning	- Release of foreign species during the release process
Contact leaching paint (Coating, known as Hard paint)	- Mechanically hard - Low cost	- Short life cycle - Poor release control - Thick leached layer - Not linear release - Must be applied in dry dock - Biocides in contact leaching paint may have a negative impact on the environment. - The leached layer creates problems when repainting the vessel - Cleaning results in a bigger release of biocides	- Better biocides	- Laws/ regulations on the use of biocides - Better biocide release systems (CDP, Hybrid, SPC)
Controlled Depletion Paint (Coating, CDP)	- Hard - Good volume to solid - Low cost - Used today	- Poor biocide release system - Increased roughness due to the leached layer - Oxidizes in air - Leakage of biocides - Used stronger biocides than alternatives (Hybrid, SPC) - Biocides in CDP may have a negative impact on the environment - Cleaning results in an increased release of biocides	- Better biocides - Price is the main factor when choosing antifouling coatings	- Laws/ regulations on the use of biocides - Better solutions for biocide release

Antifouling Technology (Description)	**Strengths**	**Weakness**	**Opportunities**	**Threats**
Self-Polishing Copolymers (**Coating, SPC**)	- Well controlled biocide release rate - Long docking cycles - Very efficient - Most commonly used today - Well known on the market	- Biocides in SPC may have a negative impact on the environment - Cleaning results in an increased release of biocides - Expensive	- New biocides - Regulations on cleaning - Increased fuel price may increase the demands on efficient AF	- Regulations on biocides - Better biocide release systems
Hybrid (Coating, SPC + CDP)	- Cheaper than SPC - Efficient, controlled biocide release	- Biocides used in hybrid paints may have a negative impact on the environment - Cleaning results in an increased release of biocides	- New biocides - Regulations on cleaning - More specific in choosing AF coatings may increase the use of hybrid in medium fouling areas	- Regulations on biocides - Better biocide release systems
Fouling release (Coating without biocides)	- Environmentally friendly - No biocides - Long lasting effect - Easy cleaning - Used solution	- Fragile - Demands relatively high speeds - Must be applied in dry dock - Hard to apply - High initial coast - Not as efficient as SPC	- Laws and regulation on biocides might become more strict - Environmental concerns are increasing (more aware costumers) - A lot of research is done on AF - Good alternative with cleaning/ grooming	- Environmentally friendly biocides - Not as efficient as needed at low speeds.
Ultrasound (Experimental method, a complementing technique)	- Biocide free - Easy to use - Cheap preventing technique - Decrease the maintenance needed on the vessel	- Sound polluting for marine animals - Needs more verification/ research	- Possible to apply on vessels any time - Laws and regulation on biocides might become more strict - No restrictions on ultrasound devices so far known to the authors	- Possible regulations of sound pollution

Summary of SWOT

Today's solutions have a number of drawbacks, the main problem is however to combine high performance with low environmental effect. This offers an opportunity for the development of the more environmentally friendly fouling releases coatings. Future regulations will probably be stricter, further limiting the use of biocides. This, in combination with few new biocides introduced to the market will result in the difficulty to further increase the performance of antifouling paints. In the near future, antifouling paints will, however, continue to dominate the market since fouling release coatings do not offer any protection against marine fouling when the vessel sits idle. It is during the idle periods that the vessel is the most vulnerable to marine fouling and this has been identified as the main weakness for fouling release paints.

The different cleaning systems mentioned offers only a complement to the solutions used today and will probably gain increased attention in the future. Since they tackle the early stages of marine fouling and can be used while the ship is in port, the cleaning solutions both extends different coatings performances' while they also offer a bridge technique until a better solution, closer to the ideal, is invented. The problem with the ships' very limited time in harbor and their very narrow time span for cleaning is a problem yet to be solved.

GAP

The purpose of the following GAP-analysis is to get an understanding of what's missing between the ideal antifouling solution and what is out on the market today. This is done, in order to show the direction in which new antifouling solutions should be researched and developed.

The ideal solution is based on the definition in Geoffrey Swain's article *Can Biomimicry and Bioinspiration Provide Solutions for Fouling Control?* (40), and have been altered by the authors to include all types of antifouling solutions.

- **Cost effective.** Fouling is a problem for shippers due to the increased drag that results in higher fuel expenses. The price and cost efficiency of the solution are everything that matter in the end.
- **Don't interfere with the smoothness of the ship hull**. The coating should not cause drag by itself. It has to be hydraulically smooth.
- **Control all types of fouling for the lifetime of the vessel.** Shippers used to be satisfied if hard fouling was treated, but the situation has changed. In the future, all types of fouling have to be prevented to minimize the fuel consumption.
- **Be environmentally compliant.** Past solutions have had unacceptable environmental effects and a future solution has to be environmentally friendly. It is also important to predict and meet future regulations.
- **Control invasive species.** The spreading of invasive species is threatening sensitive native ecosystems. It is also a big expense due to damage of man-made objects and structures.
- **Be easily applied, used, repaired and maintained.** Time-consuming repair work cannot be allowed. A ship has to be in water to be able to fulfill contracts. If a damaged section on the hull cannot be repaired without extensive work and downtime, the solution is a poor one.
- **Be compatible with the materials and methods of hull construction and decommissioning.** The industry is slow moving and rather conservative. Hence a product that isn't compatible with the construction standards of today will have a tough time before it gets trusted and implemented.

To analyze the gap, all techniques used today were seen as one. In other words, the ideal solutions were compared to the combined, positive properties, of the techniques available on the market of today. This was done in order to see what's missing. At the same time, trying to see if the combination of techniques used today could prove to be a future ideal solution.

Ideally	A future solution **should be cost effective.**
Today	A typical vessel consumes *150 tons* of fuel a day and fouling can increase the fuel consumption by up to *40 %*. This makes an effective antifouling protection vital, in order to save large amounts of money. A more expensive coating is better suited for a global fouling climate but also less environmentally friendly. In order to choose the most efficient coating, a ship's specific trade route has to be studied since this is one of the main parameters in order to select the proper coating.

Ideally	A future solution **shouldn't interfere with the smoothness of the ship hull.**
Today	A good reduction in drag is achieved by fouling release coatings. However, the demands steadily increase when the shippers continue to investigate in their ships performance. This is done by collecting data on the power consumption of a ship, which is proportional to drag.

Ideally	A future solution **should control all types of fouling for the lifetime of the vessel.**
Today	This is not achieved by any solution. Cleaning can keep the vessel in good shape from all types of fouling, but the fouling process in itself is never prevented. Macrofouling is prevented by solutions available today, however the microfouling and the forming of the biofilm is only recently investigated and partly prevented by novel coatings.

Ideally	A future solution **should be environmentally compliant.**
Today	If only considering the direct effect on the environment, an environmentally compliant solution is **today** achieved by a fouling release coating or by using cleaning or grooming on hard paint without biocides. However, the effect of insufficient fouling control is increased fuel consumption, resulting in increased emissions. To find an environmentally friendly solution, both the coating itself and the resulting fuel consumption, has to be compared and evaluated. Important to notice is also that cleaning is only environmentally friendly if done the correct way, when invasive species are prohibited. Information considering the balance between biocides and emissions has not been found.

Ideally	A future solution **should control invasive species**
Today	There is an imminent risk of spreading fouling organisms with today's solutions. To control invasive species, the ship hull should ideally be free from fouling. **Today,** only macrofouling can be completely prevented, even with the most effective anti-fouling coatings. Thus, there is a small risk of spreading microfouling organisms.

Ideally	A future solution **should be easily applied, used, repaired and maintained.**
Today	Paint is easy to apply but has to be done in a dry dock. It is therefore not possible to use once the vessel is in water. Cleaning/grooming systems, used externally, could be used anywhere but requires experienced operators and the ship to be docked. There is no solution that fulfills all the requirements.

Ideally	A future solution **should be compatible with the materials and methods of hull construction and decommissioning.**
Today	Most of the methods available today are compatible with the shipping construction and decommissioning.

Summary of GAP

By conducting this GAP-analysis we can conclude that additional research is needed in many aspects of antifouling. The most daunting fact is the ***lack of a generalized and common performance test*** in order to measure an antifouling solution's effectiveness. Suppliers of antifouling products evaluate the performance of a product in their own setup of tests conducted in-house and on the track record of the product to guarantee and state the product's performance. This makes it hard to compare different coatings.

To achieve an ideal antifouling coating the problem with the biofilm formation has to be tackled and solved. A novel solution should also focus on limiting the use of biocides, but still combat marine fouling efficiently. A study of the environmental effects of fuel reduction in comparison to the potential hazards of biocide release, and the effect of invasive species, would be much appreciated in order to evaluate what a sustainable fouling prevention system would include. Studying this should also help in the evaluation of biocides and the approval of new ones, and to help clarify to what extent they should be used. A future solution, according to the analysis, has to allow for easy maintenance, preferably while the vessel is still in the water. However, important to notice is that laws still require the vessels to dry dock with some years interval for insurance policy and overall maintenance. But since time is money, a coating that only requires to be applied once in a lifetime of the vessel, is desirable.

Future solutions according to the industry - Concluded after meeting with I-tech and International Paint, two antifouling solution providers

Biocides will continue to play an important role for antifouling solutions - at least in the near future. The main thing to consider in the development of novel fouling release and antifouling coatings is performance. This could not be emphasized enough. Fouling solutions is all about performance. Future solutions not only have to handle the fouling itself but also form a surface that decreases the overall drag of the vessel. The price of fuel is predicted to remain the highest cost for shippers. Therefore, demands for more efficient products are increasing. The regulations in the area of antifouling solutions are still changing and to keep track on the development of laws and regulations is important for the development of future solutions.

Environmental concerns regarding the coatings are important, but to really understand the problem and to develop future coatings that can be considered environmentally friendly, the entire complexity of the problem has to be considered. Both the direct effect of the biocides but also the effects of increased emission if a vessel's drag would increase are part of the problem. The society is striving for more and more environmentally friendly solutions, something that has not yet been seen in the shipping industry since they are still all about performance.

The development of new biocides is a very slow process and Clayton Price, technical manager at International Paint, is sceptic about the likelihood of new biocides to pass the European regulations at all, the only biocide he is positive about, concerning approval in EU, is Selektope, developed by i-tech.

Future Ideas

Based on the previous SWOT and GAP analysis the requirements for a future solution were identified. It was also clear from the analysis what today's solutions are missing. The gathered knowledge constituted to a knowledge foundation that was used to generate novel ideas to solutions to marine fouling.

Today's solutions can all be thought of as a poor attempt to a standalone, issue free technique that hope to solve all the shippers problems with marine fouling. The major problem with today's solutions, and will continue to be for a novel solution, is to achieve a high performance with low environmental effects, combined with the compliance of laws and regulations. The solution should then, ideally, provide the vessels with a fouling free hull for the entire lifetime of the vessels, something that none of today's solutions manage to achieve. Solution providers fail to see that today's solutions are not working and that a different approach should be suggested. A good attempt are done by novel cleaning solutions emerging on the market. Cleaning is an external solution thus the solution's lifetime is unrelated to the ship's lifetime. This means that as long as the cleaning solution is maintained, the vessels will have a fouling free hull. What cleaning offers can be thought of as an external stimuli, and is an approach that is implemented in several of the following ideas, examples are; UV-light, electric field and electric current to prohibit the fouling process. It is an approach we strongly believe in but what should not be forgotten is that a future solution should also be cheap and robust, something that some of the following suggestions fail to address. In total, nine ideas were selected out of a hundred generated, and viewed as the most promising novel solutions to marine fouling that we were able to identify. Since the use of biocides are well investigated and not environmentally sustainable in the long term, all ideas presented are based on alternative ways of preventing the fouling process. In the following, each idea is described, followed by a short text from the quick research that was done. The ideas are:

- UV as Disinfectant
- Titanium Dioxide and UV-light
- No Hard Surface
- Conductive Paint
- Hull Cover
- Electric Field
- Coating with UV-light
- Affect the Hull with Outside Force
- Surface Affected by Stimuli

UV as Disinfectant

Idea: UV-light could be used in combination with cleaning by killing fouling organisms and thus solve the problems with invasive species that have led to the regulations of prohibiting cleaning to be used in some harbors.

Research: UV-light has disinfectant properties by damaging the nucleic acid in microorganisms and preventing them from reproducing (82). Depending on the nucleotide of the organism, the wavelength absorption differs from *200 to 300 nm*. The composition of the nucleic acid affects the absorption peak, that tend to be near *260 nm* (82).

UV-light damages the germ plasm of the microorganism, which will leave them unable to perform vital functions. Important to know is that many microorganisms can repair the damage caused by UV-light by using enzymes (82). The nucleic acid repair can be divided into two kinds, photo-repair and dark repair. Photorepair is when a repairing enzyme gets activated by the exposure to light between *310* and *490 nm*. Dark repair is any repair process that doesn’t require the presence of light and most often sets in right after the UV-exposure to repair any damaged nucleic acid (82).

According to the U.S Environmental protection Agency Office of Water, UV-disinfection is an effective method for freshwater cleaning, if used correct, even when the microorganisms have repair abilities (82). The question still remains, is it capable to prevent foreign species from inhabiting new areas and reduce settling on ship hulls as well?

Photo-repair can be prevented by keeping the water in the dark for two hours after the UV exposure. This is of course not suited for an antifouling application. The dark repair is not a problem in drinking water applications since it contains so few organisms. But again, this may cause a problem for UV-cleaning when used for cleaning ship hulls in sea-water. If the UV-light exposed microorganism have the ability to repair themselves, right after the exposure, invasive species will most definitely spread.

Anders Rulander at *Watersprint*, a company that offers a novel water cleaning method using UV-light, state that a high enough dose of UV-light results in breaking the nucleic acid in so many places that it is unable for it to repair itself, thus, it would be possible to prevent invasive species with UV-light. Based on this, high intensity at several wavelengths of UV-light could be used to kill fouling organisms on ship hulls and be used as complement when cleaning.

Titanium Dioxide and UV-light

Idea: Coating ship hulls with titanium dioxide combined with natural light and external light-sources, should result in a self-cleaning hull due to the self-cleaning properties of titanium dioxide.

Research: Titanium dioxide work as a photocatalyst by absorbing light with energy corresponding to the bandgap (83). This results in the generation of an electron-hole pair when the absorbed light has enough energy, corresponding to either the bandgap of titanium dioxide or greater. The electron-hole pairs may either recombine or take part in a redox reaction. Titanium dioxide can, due to this effect, decompose organic contaminations to CO_2, H_2O, NO_3 or other basic products under UV-illumination (84). Today, it is also possible to dope titanium dioxide, making the band gap smaller and reducing the required energy allowing for visible light (wavelength > *450 nm*) to achieve the photocatalytic effect (85).

By combining a surface with self-cleaning properties with external UV illumination, the technique might combine the properties of, ‘easy to use’ and ‘eliminate all fouling organisms’.

Advantages

- Self-cleaning
- Superhydrophobic
- May result in a new, more effective cleaning method of hulls coated with titanium dioxide
- Titanium dioxide is extensively studied and commercially available
- Disinfectant

Disadvantages

- May demand too much light for efficient self-cleaning
- Uncertain method
- Don’t **prevent** fouling, only **removes**
- A too heavily fouled hull may prevent the light from reaching the titanium oxide

No Hard Surface

Idea: Coating the ship hulls with a surface that makes the fouling organism unable to feel or see the vessel.

Research: The basic concept of this idea is to remove any hard surface for the fouling organisms to settle on. By replacing the solid (hull) – liquid (seawater) interface with a liquid – liquid interface, the fouling organisms should be unable to settle. For the idea to work the liquid, in contact with the water, has to be unattractive and not allow penetration by the fouling organisms. That should, in theory, result in fouling-free ship hulls. This is a three step solution with two interfaces of interest, the interface between the hard ship hull surface and the intermediate liquid and the interface between the intermediate liquid and the seawater, illustrated in Figure 15.

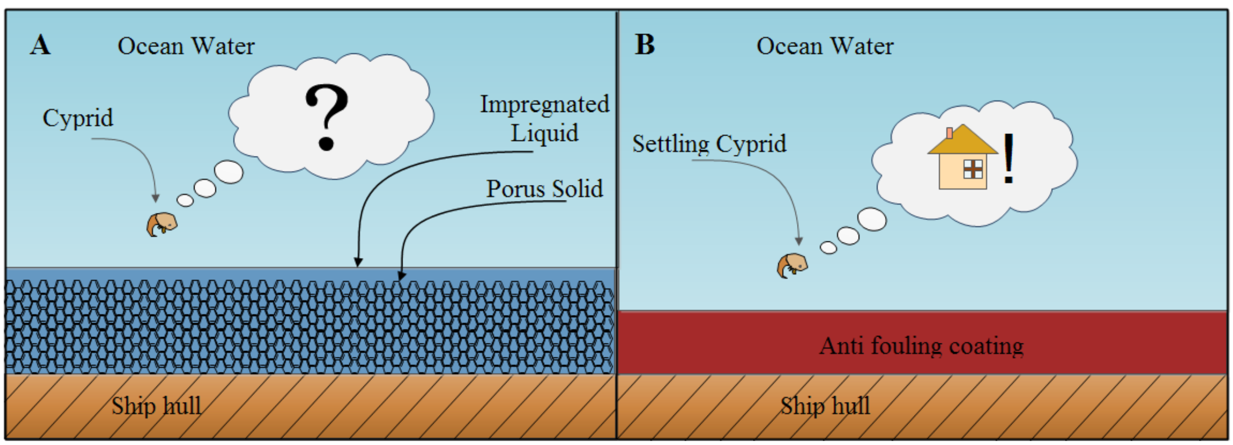

Figure 15 A) a cyprid looking for a surface to settle can only feel another liquid interface, a surface unattractive to settle on. The impregnated liquid stays in place, close to the ship hull thanks to the porous solid. B) A cyprid finding a perfect place to settle.

After a quick search on the Internet, a company that uses a technique, similar to the idea described above, but for other applications, was found. Their product is called LiquiGlide and two papers have been published describing their discoveries. They describe LiquiGlide as a “permanently wet, liquid - impregnated surface which is designed to be hyper-slippery and the product sits on a layer of liquid” (86). Their solution is a two layer construction; the first layer, a highly textured surface that’s used to stabilized the second layer which is an impregnating liquid that fills the textured surface, see Figure 15. Other liquids, in contact with LiquiGlide, will slip on the impregnated surface.

Another technique, that also shows promising properties is the so-called *slippery liquid infused porous surfaces* (SLIPS). It is a very similar technique compared to the above-mentioned LiquidGlide. SLIPS uses a combined porous/textured solid with their lubricating film instead of a squared-shaped pattern like LiquidGlide. The main difference is that it is researched as an **antifouling material** at Harvard, *School of Engineering* and *Applied Science*. Contact has been established in order to learn more.

Advantages

- No hard surface for organism to settle on (no fouling)
- Slippery surface - very low friction (low fuel consumption)
- Biocide free. Environmentally friendly, due to low fuel consumption and no use of biocides

Disadvantages

- May require more advanced application techniques
- May be sensitive
- Might be hard to contain the impregnating layer
- Does it work for a wide range of organisms?

Conductive Paint

Idea: Coating the ship hull with a conductive paint in order to alternate the voltage and make the attached foulers come off.

This is a possible solution found in the article *Prevention of marine biofouling using a conductive paint electrode* by Tadashi et al. (87) from 1998. Even if the article showed very positive results, no further research by the authors have been found. The idea was nevertheless picked up because of the promising results and lack of ongoing research.

Research: The article describes an electrochemical disinfection achieved by a conductive paint on nylon-based fishing nets. The result from applying a potential of *1.2 V* was completely killing all the attached cells (v*ibrio alginolyticus*). A negative voltage of *-0.6 V* followed, which resulted in the detachment of the cells. In vitro experiments were also conducted with promising results (87).

In order to have the antifouling solution to prevent fouling efficiently, the entire area of interest has to be conductive. The obvious problem with this will come from the behavior of the current. Naturally, it always takes the easiest way, the one with lowest resistance. Fouling organisms are believed to increase the resistance locally when settling on a surface, thus avoid the current. Another problem might be that the solution, if applied to ship hulls, would interfere with the ships corrosion protection system (35).

After discussing this method with Dr. Petrone, a Senior Research Fellow at Nanyang Technological University we came in contact with during our research, the question about the nature of the organisms used in the initial experiments was highlighted. Some microorganisms show attraction or repulsion against negatively or positively charged surfaces. It was therefore concluded that the used organisms in the experiment may have deliberately been chosen only to illustrate repulsion.

Advantages

- Previous research has shown very promising results
- Seems possible to combine with paint techniques used today
- Environmentally friendly

Disadvantages

- May interfere with the corrosion protection of the ship hull
- Requires a direct current
- Hard to implement on large surfaces
- Fouling may reduce the effect of the antifouling properties

Hull Cover

Idea: Covering the hull during idle times allows for the protection of the vessel.

It is of special interest in high fouling areas during idle periods since this is when a vessel is as most vulnerable.

Research: The fouling on ship hulls is most severe when the vessel is idle. A solution for vessels when anchored for longer periods, would be to completely shield the vessel from the surrounding seawater. By creating a protective barrier around the vessel, the fouling should be efficiently prevented. If the protective environment would be constructed like a second skin the water volume inside the protective cover becomes very small and can in turn be treated to prevent fouling. The basic concept of this idea is that by removing fouling organisms, nutrition and light, the fouling process can be prevented. How the water inside the protective cover should be treated, has not yet been evaluated. Some possible ways are however presented below.

- Filter the water and remove all nutrition and fouling organisms
- Increase the salinity
- Use UV-light to clean the water
- Biocides (Will work in a closed environment, thus not toxic for the surrounding)
- Heated water
- Exclude light from the hull

Advantages

- Protects the vessel when it is most vulnerable to fouling
- Can be made environmentally friendly
- Can protect against spreading of invasive species
- Can be made very efficient

Disadvantages

- Takes time to apply and remove at every docking
- May require external systems for filtering the water or removal of foulers
- Fouling on the protective shield
- Only protects the vessel when docked

A similar product, to what is described above, is the Swedish invention *Protectocover* from a company called *Cleanboatprotector*. It is an easy, yet ingenious product for small boats up to 10 meters. A "plastic carpet" is placed in port that you let the vessel slide up onto when docking. The carpet will form itself around the hull, shutting out sunlight, oxygen and nutrients, essentially everything that foulers need. The company state that antifouling coatings are no longer needed. It should be remembered that Swedish water qualifies as low fouling areas. The carpet will most likely also contribute to a small grooming effect, removing already adhered species (88, 89).

Electric Field

Idea: To kill foulants with a very high **electric field**.

The latest technology achievement with the fabrication of precise nanostructures has the potential to be utilized for marine fouling applications using electric fields. With the electric field equation

$$E = \frac{U}{d} \tag{1}$$

we can see that with a voltage, *U*, and a really small distance, *d*, we are able to generate a large electric field, *E*. An electric field with the amplitude in the gigavolt-per-meter (GVm^{-1}) region might be high enough to eliminate fouling organisms. It is not clear if a surface emitting such a high electric field should cover an entire ship hull, or, be used as a complement to today's cleaning devices.

Research: The articles found covering this topic are mostly from the beginning of the millennia, foreseeing the use of electric fields, or pulsed electric fields, to prohibit marine fouling (78, 90, 91) . The use of electric fields to prevent fouling has mostly been investigated with regards to being used as filters at the entrance of cooling water systems. At first glance, using a constant electric field as a way to prevent fouling might seem to be a very energy inefficient way. Research shows that the same effects, or even better, can be obtained with a pulsed electric field (PEF). By lowering the electric field and use a series of pulses rather than a single, the same effects might be expected. Tests have shown that PEFs provide full protection against biofouling when pulses of *77 µs* long, and 6 *kV/cm* in amplitude, are used in an inlet of a water cooling system. The electric field is causing temporary immobilization of the organisms. This effect is believed to be caused by reversible membrane breakdown. Pérez-Roa et al. (78) show that PEFs had a 95% prevention of barnacle cyprid settlement. Their results showed that the variation in spacing between the electrodes didn't have any effect on settlement behavior (78).

It has been shown that nsPEF (nanosecond Pulsed Electric Fields) is caused to induce programmed cell death (apoptosis) (91). It was demonstrated in cultured cells, but it sure agrees with Abou-Ghazala's et al. (90) hypothesis that the duration of the pulses shift the location of the cell damage. From a microsecond to a nanosecond pulse, you'll shift the damage sight from outer membrane to the nucleus of a cell (92).

Advantages

- Technology available for further improvement
- Very good initial results

Disadvantages

- Advanced technology
- Fragile surface
- Some challenges to conquer with scaling

Coating with UV-light

Idea: UV-light emission outwards from the **ship hull** surface.

Benefits of UV-light have been rediscovered and the area of use is increasing due to the latest technology developments in UV-LEDs. If ultra violet (UV) light is created with the LED technology, instead of common fluorescent tubes, the light sources can become smaller and be used in new applications (93). UV-LEDs are also beneficial since they are less fragile and more energy efficient compared to the fluorescent tubes. One question is if you can have UV-light emitting from the ship hull surface instead of the other way around. Then, you would have all the benefits from UV-light and not be limited to a stationary platform.

By placing a ledge consisting of UV-LEDs along and around the ship hull, parallel with the water line, fouling might be prohibited. Lightguides, like optic fibers, will spread the UV-light from the source, and out across the entire ship hull for an even emission distribution, illustrated in Figure 16.

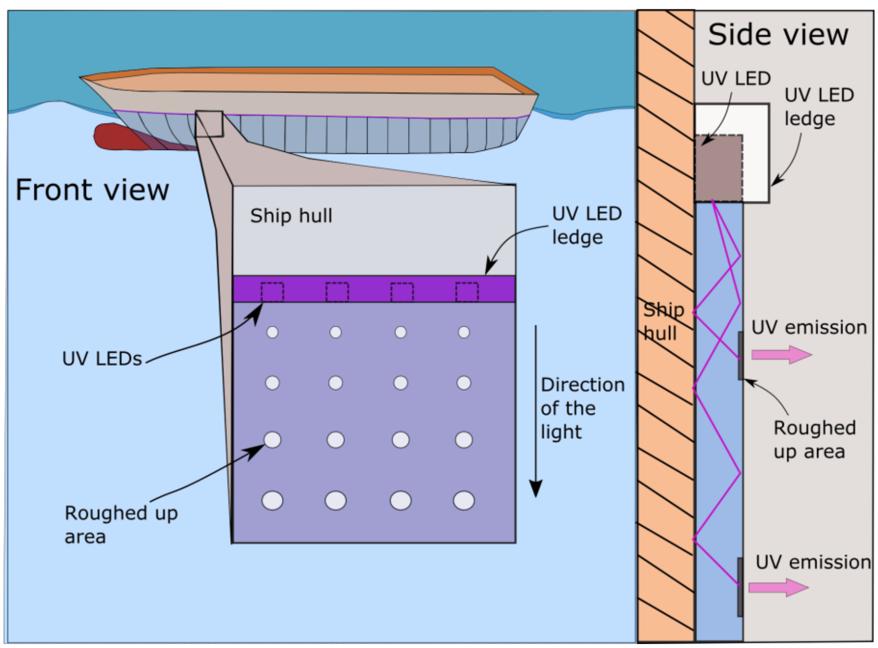

Figure 16 To get UV-light emitted from an entire ship hull surface, a ledge containing several UV-LEDs will emit UV-light into a sheet-waveguide. The waveguide will have roughed up holes where light will shine through. Also, the holes in the surface of the lightguide will have to be designed with different sizes depending on their distance from the light source in order to spread the light evenly.

Research: Lightguides that are low cost, large, flexible and very thin, formed as a sheet, have been produced. These can be used to spread the light from UV-LEDs over the ship hull surface. To make the UV-light shine outwards from the hull, spots can be created in the shape of holes by roughening up the area in order to change the angle of the surface, see Figure 16, Side View. If the coating is thin enough, it could be made bendable and could be formed around the hull. The internal absorption within the material will make it hard to efficiently spread the light over an entire ship hull. Conducted tests showed for example that PMMS has an internal absorption of about *0,3 %* per millimeter (the length of the lightguide was *340 mm*) (94). Thus getting the light from the source to the end of the lightguide, if the length equals the depth of a ship hull, will prove difficult. Another problem with this method will be to evenly spread the light across the surface. The light emission will be most intense, closest to the light source. One way to solve this is to have different hole sizes on different locations, of the coating. Smaller holes closer to the light source, and bigger, further out, will create an even light emission (94), see the growing hole size illustrated in Figure 16, Front View. A problem with covering the ship hull with UV-LEDs and lightguides is the fragility of the coating. The smallest cut or tear will damage the coating and make the light leek, resulting in dark patches not emitting any UV light (95).

The International Congress on Marine Corrosion and Fouling 2014 in Singapore had an invited speaker that presented a similar approach. Under the category - New Approaches for Antifouling, Bart Salters presented his talk - *Prevention of Bio-fouling by using UV-light emission outwards from ship hull* (95). This is a project by Philips that started two years ago. Instead of using the coating as a lightguide (described above), they present a coating with the UV-LEDs incorporated in it, where the LEDs have a distance of *5 cm* from one another. The first test that was conducted with the UV-LEDs submerged in seawater showed promising results. Not a single organism managed to survive on the surface around the UV-LEDs (96). The optical power output equals $0{,}1\ Wm^{-2}$, resulting in the power consumption of a few water boilers if you were to dress a $10.000\ m^2$ hull (95), which would be equal to a trade ship.

Advantages

- 100% effective
- Low power consumption
- Able to fabricate large surfaces thus cover large areas

Disadvantages

- Fragile surface
- Assumed hard to repair
- Unknown lifetime
- Unknown if sustainable
- Unknown price and how is it applied to the ship hulls?

Affect the Hull with Outside Force

Idea: Affect the hull with forces from the outside using air bubbles combined with UV light, where the bubbles might act as lightguides for the UV-light.

The original idea came from the above idea, *make the ship hull invisible*, see No Hard Surface. By trapping air bubbles between the surface of the hull and the water, you would turn the solid/liquid interface into gas/liquid, and the organisms would be unable to settle. Discovering it as a technique used by dolphins to stay clean, confirmed that it might work on ships. They tend to jump up and down in the water to trap air bubbles along their skin. The topography of the dolphin's surface makes air bubbles stay trapped longer and create a "reversed lotus effect" as they fall off. Instead of water droplets sweeping of dirt, as for the lotus leaf, you now have air bubbles scooping of dirt along the dolphin's surface. Our hypothesis is that a produce constant flow of air bubbles along a ship hull surface would reduce fouling.

A second thought that occurred to us was to use the air bubbles as lightguides, or rather like light packages. If UV-light would shine into the air bubbles, as they formed, the bubbles would then upon impact with the hull, release UV light and kill off foulants. A later thought, with some knowledge about lightguides, makes us realize that it would not work. For total internal reflection to work, the surrounding medium should have lower refraction index than the core. Since air has *1*, and water *1,33* in refractive index, we purpose the UV-light would leak right through without being trapped in the bubble.

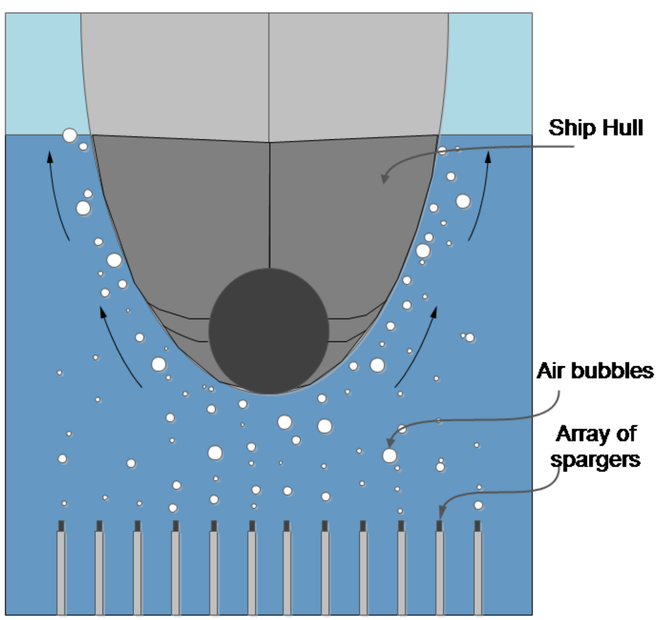

Figure 17 **An array of spargers, placed underneath a vessel as it sits idle, will release a constant flow of air bubbles that will reduce fouling.**

Research: Field studies in tropical water have been carried out where they let both submerged panels and one patch of a ship hull, be exposed to curtains of air bubbles. The ship, coated with *Intersleek 900* (a fouling release coating) was stationary for 3.5 months in a high fouling area. The air-spargers where placed roughly *3 meter* below the water line followed by an air supply of *8* $lmin^{-1}$, see illustration in Figure 17. The result was promising according to Scardino et al. (97). The patch of the hull, exposed to air bubbles, was limited to fouling with slime (90% cover) and other soft fouling species such as *hydroids* and *erect bryozoans*. Some, but very little, hard fouling was reported. Compared with the control zone, that had much more hard fouling (28% *spirorbis tubeworms* and 39 % *encrusting bryozoans).* The result demonstrated that this technique could be used as a complement to fouling release coatings whilst the vessels remain static (97).

A similar investigation was also found using submerged PVC and concrete panels (97). The panels were placed only *0,5 m* above the spargers, panels with the size of *10 cm x 10 cm* and placed directly above the airflow, this time with a rate of roughly *3.3 to 5,0* $lmin^{-1}$. After one week of submersion the aerated surface had roughly *0,1 %* of the number of settlers as non-aerated control panels. After four weeks, they found that the aerated panels had only *~4,0 %* of the mass of fouling compare to the controls. The results clearly suggest that aeration could be used as an effective way to control biofouling and is also supported by previous results (98).

Advantages

- Could be incorporated in harbors
- Easily scalable, suited both for small and large vessels
- Could be used with today's somewhat simple technology
- Environmental sustainable
- Offering a solution whilst stationary
- Requires somewhat homogenous hull structure

Disadvantages

- Uncertain effects
- Conducted test (with only air bubbles) hasn't proven that effective
- Must be used as a complemental solution
- Energy costs unknown

Surface Affected by Stimuli

Idea: Topographical surface changed by natural stimuli in order to remove fouling.

Looking at our own body we have structures that are able to release and transport microscopic particles. It surely is more than just a structure but if you think about the cilia in your throat for instance, they do a great job transporting and keeping your respiratory tract free from air bound particles. It is mostly due to the mucus, but also, the movement of cilia transporting particles out of your body (99). If we were able to replicate the cilia-like structure and force them to move, they could be placed on a surface much like a ship hull and prohibit settlement and growth of a biofilm.

Research: At first glance it seems to be a brand new field and not many articles published. Rajat et al. (100) speak about the development of microfluidic channels that encompass synthetic cilia to still be in its infancy. Via computational modeling they are able to replicate the movement of oscillating, synthetic cilia and how they affect microscopic structure in a fluid-filled microchannel, see illustration in Figure 18. Their model showed that depending on the frequency of the beating cilia the particle can be either driven down- or upward from the substrate (100). There has been a successful attempt of replicating a cilia-like structure. B.A Evans et al (101) actually managed to produce structures with the same size as a biological cilia (~*10 µm* in length, ~*200 nm* diameter). By creating a composite material of PDMS and iron oxide nanoparticles, they managed to create superparamagnetic rods, which they are able to actuate by applied external magnetic field.

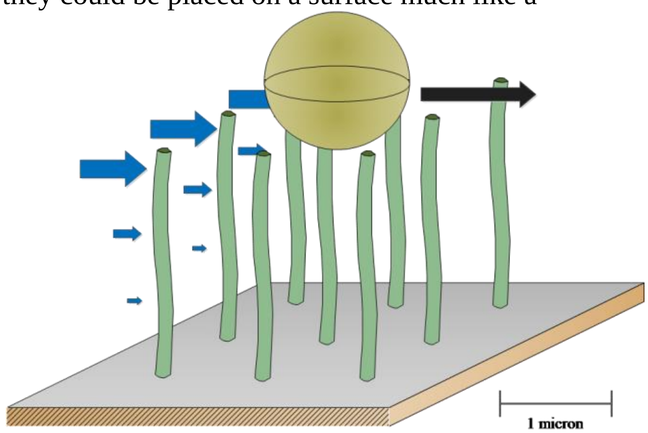

Figure 18 Cilia-like structures have successfully ben reproduced. If movement is applied, the cilia-like structure can either transport particles downward or upward. The scale bar is one micron.

Advantages

- A non-biocidal solution
- Bioinspired movement caused by external stimuli

Disadvantages

- Unknown effects on fouling community
- A brand new type of research
- Might affect the hydrodynamics negatively
- Fragile surface

Conclusion and Discussion

After hundreds of years of research and technology breakthroughs in antifouling solutions, fouling is still a problem for modern vessels. The world's transportation is predicted to increase with an increasing population. Since 90% of the transport of today is by sea, an ideal antifouling solution will be of great interest for shippers and the society in order to decrease our environmental footprint.

The main techniques used today, and in the past, are biocide release systems. What has shifted over the course of history is what toxins are put into the biocide release system. The environmental effects of the biocides have gained increased attention, especially since the ban of TBT that have had extremely severe effects on the aquatic environment. For the near future the situation, and the use of biocides, will most probably not change due to the lack of cost-efficient and high-performance alternatives. However, in the long term biocides are not a sustainable alternative, a fact that both shippers and coat manufacturers as well as the authorities, agrees on.

The development of novel biocides is an extremely expensive and long process. In contact with the painting industry they even expressed the process so demanding that there will not likely be many, if any, biocides approved by EU in the near future. This could stop new and more environmentally friendly biocides, compared to the ones used today, to be introduced to the market. Future regulation may also be developed considering the amount of biocides released. For vessels to enter European waters their antifouling coating has to be approved by EU. This forces the global shipping companies to follow the more strict EU regulations. What's also positive is that smaller countries look to the stricter regulations set by EU when considering their own.

Bioinspired solutions have focused on finding the Holy Grail among marine animals that can work as a model organism for a novel coating. Doing this may prove successful, however, it is important to notice that no marine animal rely on only one single solution in order to prevent fouling on itself. Instead, it is a combination of many different techniques that together provide an effective fouling protection. Combining different antifouling solutions have gained more attention lately. For example, according to Wallenius Lines, we will probably see more combination of hard paint and regular cleaning in the future, when cleaning methods are improved.

You can successfully argue that nature has worked as an inspiration for at least some potential antifouling solutions. Products like Sharklet, LiquidGlide and SLIPS are inventions that all look promising but needs both more funds and more research. The process of developing an antifouling solution is difficult and requires a large amount of data before its performance can be guaranteed; data you receive by testing it in real life situations. This is a problem because the shipping industry is known to be rather conservative, not precisely jumping for untried antifouling solutions. The cost for a failed antifouling solution will always be tremendous for the company in question due to lost income while the vessel is in port. Novel and more creative solutions will most likely have to be proven to work on leisure boats before used on larger trading ships since a failure will not be as costly.

One of the largest problems, according to us, is that the antifouling community lacks a common and good evaluation procedure for new antifouling solutions. Today, tests are generally performed in-house by the companies themselves, with their result later backed up by a convincing track record. Thus a product's effectiveness is very hard to compare to other products since stated data is based on tests unique for every manufacturer. This secrecy complicates for both novel solutions and new companies to enter the market. A standardized measuring system for an antifouling solutions effectiveness is no easy task since it depends on a vast number of variations, but it is clear that more has to be done. We would like to see a collaboration with both the major painting industries and shippers as well as the International Maritime Organization to solve this issue and decide on a standard that is easy to compare. Why this is yet to happen can only remain speculations. The obvious reason seems to be the legacy from the era of TBT still makes itself reminded. With such an effective product there was really no reason to develop standardized comparison.

Most of the products used today are succeeding in preventing hard fouling, however, the soft biofilm is still a major issue and involves a lot of work. The shippers used to be satisfied by combating hard fouling but due to the increasing knowledge and research, they now also begin to demand a product that prevent the biofilm formation. Important to notice is that there are no biocides available to prevent the growth of a biofilm. *International paint* recently introduced their *Intersleek 1100 SR* (a biocide free, fouling release coating) that is one of the first products to hit the market that, according to themselves, makes it possible to control and prevent some of the soft biofilm. At the time of writing we see an increase in products from the major paint companies they call Fouling Defence. It is supposed to be a combination of both a biocidal system and a fouling release coating, combining the better of two solutions.

According to Wallenius Lines, fouling release systems are the solution most similar to the ideal solution. However, the coating is still hard to attach to the ship hull and pose the risk of contaminating the dry dock and its surrounding vessel in that sense that it makes all the surfaces it comes in contact with to become super-slippery, an obvious problem for surrounding vessels trying to apply other types of coatings. As a result, only a few dry-docks around the world are willing to perform fouling release paint jobs. Another approach we will most likely see more of, according to Wallenius Lines, is to combine hard paint with closed-loop cleaning systems. The risk of invasive specious can be eliminated by closed loop cleaning systems and cleaning can be used more often and on more locations.

In the long run, the focus will shift from the fouling of the vessel to its overall smoothness and the drag it causes. This is when the fouling control is so efficient that the smoothness of the vessel affects the drag more than the fouling. Today, the effect of fouling is still one order of magnitude bigger than the effect of the vessels smoothness. It doesn’t matter if the drag is caused by fouling or the coating, the drag must always be reduced to a minimum in order to decrease the fuel consumption.

Nanotechnology has been identified as a key area that may hold the answer to the problem with marine fouling. How nanotechnology should be used is never stated in this ongoing discussion. With some insight in both the field of nanotechnology and antifouling solutions, we offer two thoughts worth noting. First of all, if you have something very small and accurately designed for a specific task, like a nanostructure, it will often be more fragile than a corresponding larger structure. The properties of a nanostructure is also most often related to its well-defined shape and structure, thus if being damaged, its abilities to fight fouling will most likely be reduced. Keeping a nanostructure free from breaking if placed on the outside of the hull will probably prove difficult. Secondly, to upscale a nanotechnology-based solution to be a suitable solution for a 300 meter vessel, and for a reasonable price, will perhaps be a more daunting task than to get the nanotechnology-based solution to work in the first place. However, for nanotechnology to work as a reliable solution, it has to be incorporated into something else. Still, solutions that have adopted nanotechnology are emerging. Biocyl, the fouling release coating with carbon nanotubes incorporated, is a perfect example of nanotechnology that has hit the market.

There is one surprising analogy that fits right into the problem with fouling and its solutions, and that is the one about your oral cavity (i.e. mouth) and your dental hygiene. Because if you start to think about it, we have every day the same problem in our mouth. If you don't brush your teeth, twice a day, you will get plaque from bacteria that eventually leads to corrosion (i.e. holes). All the solutions we throw at this problem needs to be environmentally friendly, meaning it should be safe for our body to taste, swallow and even eat. Let us just remind you that the radioactive toothpaste, introduced in the 1920s, was not so healthy.

If we think of our dental hygiene, there is really only two ways to stay free from tooth decay. You either brush your teeth (toothbrush) every day as you were told or you stick something onto your teeth (toothpaste), preventing the bacteria from ever settling. The latter would be the better because it means the surface will stay completely free, at all times, from settling bacteria. If you apply the same thought-strategy on fouling, and how to prohibit it on ship hulls, you'll come up with the following thought-exploded view.

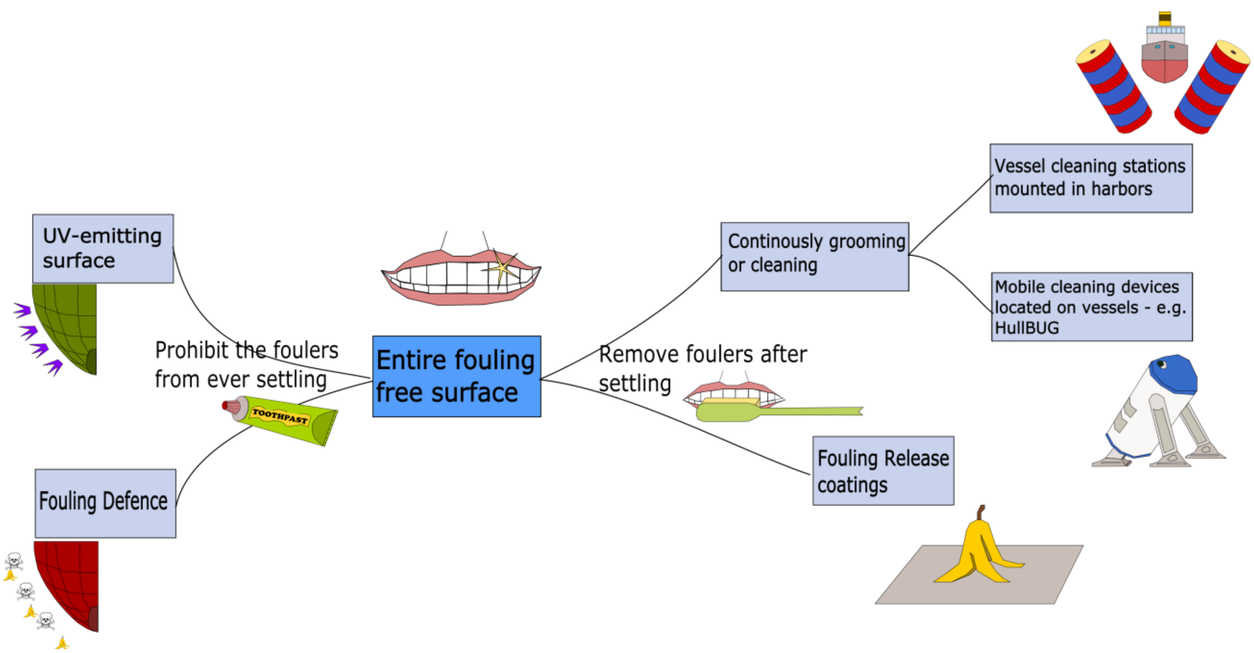

Figure 19 The thought-exploded view describes what future techniques can be implemented or combined in order to get closer to or reach a novel solution. The analogy between your dental hygiene and a fouling free ship hull is done to better understand what is needed in order to stay fouling free.

The above solutions and principles, seen in Figure 19 are what we think will be the future for antifouling solutions and get us as close as possible to the ideal solution. The future of antifouling has according to us two main alternatives to either choose or combine from. The first principle we explore is ‘Remove foulers **after** settling’. To achieve this we have to implement continuously cleaning of the hull. It leads up to the idea of a ‘boat-cleaning station’ to be used on vessels each time they enter or leave a port. It is an interesting idea and solution that could be implemented on any vessel without having them to purchase an expensive antifouling coating. However, the idea leaves some problems. The hull surface will almost never be an entire fouling-free surface, except right after a wash, leading to some drag at all time. Also, re-growth rate of foulers has proven to be the fastest right after cleaning. Another problem is the implementation of this technique. In which harbor will you install this device first? And how often will the vessel dock in a harbor that uses this form of cleaning? It will have to be installed in each and every port in the world to offer its customers a global coverage. This will initially be a huge investment. Another type of cleaning solution would be to use robots, fitted with brushes, just like the HullBUG mentioned above. Each vessel possesses a pair that they can launch on a scheduled basis wherever it is in the world. The robots would automatically groom the entire hull. We have also placed fouling release coatings under this branch. This technology is still incomplete since it doesn’t work under static conditions, thus it is not an option for all fouling situations. Fouling release coatings need a constant flow of water for foulers to lose. If a vessel sits idel too long, and macrofouling starts to attach, it could pose a problem. The second principle is ‘Prohibit the foulers from settling’. It includes the very promising technology called ‘UV-light emission outwards from the ship hull’. If it works as promised it will be the only biocidal free technology that prohibits fouling organisms from ever even settling. It will be ideal for static conditions and work just the same when the vessel is in transit. The only questions to ask is how fragile it is and how easy it is to apply and maintain, two questions that surely can be answered with more research. Lastly, we find the product called Fouling Defence that both combines biocidal system and fouling release properties, launched last year. It is a tough discussion to purpose a biocidal system as a candidate for a future ideal solution, but the combination of the two might let us decrease the amount of biocides to a minimum. If you for instance regard Selektope, the biocide invented by i-tech, it is both specific and gives the cyprid reversible effects, it can therefore be regarded as a mild biocide and would therefore be perfect for a Fouling Defence product.

Even if the above solutions are described as separate solutions they probably will be combined to offer a complete protection. Because even if we get more efficient coatings in the future we believe that in order to achieve the most cost-effective and lasting protection, not one, but several complementary methods have to be implemented.

How the future will look like is something that nobody can know for sure. The following technology roadmap is our prediction for the near future.

2014	- Fouling Defence paints are introduced to the market
2016	- The last new biocide, Selektope, is approved in EU
2025	- Propulsions systems using renewable energy sources like wind are installed on new vessels and used at a higher extent
2030	- Regulations on 'amount of biocide released' is introduced in EU
	- Increased control and more strict regulations on biocides
	- Cleaner exhaust emissions from either liquid natural gas or higher quality diesel are more common
2040	- Novel antifouling systems will have replaced every biocidal system, 'UV-light emitting coating', for instance, will be complemented by 'vessel-cleaning-stations' in most harbors

Hopefully, at the end of this road-map, if not already there, we will be a lot closer to the ideal solution.

Glossary and Definitions

Actuation – To put into motion or action; activate.

Actuation schemes – A setup or network of actuators.

Air-spargers – To introduce air or gas into (a liquid).

Anesthetic properties – A substance that induces insensitivity to pain.

Annelids - Collective name for group of worms such as earthworm or leech.

Antennule - A small pair of antenna present on the first segments of the head on Crustaceans (Collective name for group of arthropods, includes crabs, lobsters, crayfish, shrimps, krill and barnacles).

Antifoulants – A substance (such as paint for use on ship hulls) designed to prevent, reduce or eliminate fouling.

Anti-herbivory – (herbivory – the eating of plants, especially ones that are still alive) A protection system for plants to avoid being eaten.

Barnacle – A type of arthropod related to lobsters and crabs. A marine animal that tend to live in shallow and tidal waters type. They are suspension feeders and attaches themselves to hard substrates. Around 1,220 barnacle species are currently known (102).

Bioaccumulation - The accumulation of a substance in an organism. Often refers to the toxic substance or pesticides.

Biocides - Chemical or biological pesticides (not intended for plant protection) used for protection from microorganism intended to kill or deter the organism (103).

Booster biocides - Extra biocide that has to be added due to the resistance to the biocide by some organisms.

Branchiobdellid - Collection name for an order of worms.

Bryozoans – also known as moss animals. Are typically around *0.5 millimeters,* they are filter feeders that sieve food particles out of the water using tentacles. Most marine species are found in tropical waters (104).

Cavitation - The forming of bubbles containing vapor in a moving fluid where the pressure has dropped below the vapor pressure.

Charged cuticle – The charged outer layer of living tissue.

-cide - a suffix meaning killing.

Ciliary cleaning – Cleaning performed by ciliary movement.

Copolymer – A polymer derived from more than one species of monomer.

Crustacean – A large group of arthropods, includes animals like crabs, lobsters, crayfish, krill and barnacles (105).

Denticles - A tooth-like structure such as scales on shark skin.

Deterrent effects – Effects that discourages or is intended to discourage someone from doing something.

Diatoms – A major group of algae and also the most common type of phytoplankton. Estimated to contain more than 100,000 species. Can basically be found in any damp place like oceans, lakes and soils (106).

Elastic modulus – Corresponds to a number describing an objects resistance to elastic deformation.

Epibionts – Organism that inhabits the surface of another living organism and is usually harmless to the host.

***Erect bryozoans* –** A type of bryozoan, see bryozoan.

Fenton reaction – Solution consisting of hydrogen peroxide and iron catalyst that can be used to oxidize contaminants or waste waters.

Cuticle – Term for the outer (non-mineral) layer of an organism.

Flagellum – An extracellular organelle that works as a source of propulsion.

Foulants – any material that causes fouling.

Foulers – Organisms that cases fouling.

Gametes – a mature sexual reproduction cell, as a sperm or egg.

Invertebrate species – collection name for animals without a spine. For example, Mollusca and arthropod.

Lanolin – Fat extracted from wool.

Lipophilic – Means “likes fat”. Molecules that dissolve in fat are lipophilic. It is not the same as hydrophobic (108).

Lipophobic – Means “don’t like fat”. Describes molecules that don’t dissolve in fat. It is not the same as hydrophilic.

Gorgonians – An order in the coral family.

Halogenated *furanone* – A reaction with a compound from group 17 in the periodic table, replacing one of the hydrogen atoms, formed together with *furanone*.

Halogenated pyrrol – A reaction with a compound from group 17 in the periodic table, replacing one of the hydrogen atoms, formed together with *pyrrol*.

Hydroids – a life stage for most animals of the class Hydrozoa (small predators related to jellyfish) (107).

Hydrophilic – Means “likes water“. Correspond to surface with a high surface energy on which water spreads.

Hydrophobic – Means “don’t like water”. Surface with a low surface energy on which water don’t spread but instead forms a spherical drop on the surface.

In vitro – An in vitro study refers to a study of cells or molecules studied outside their normal habitat.

In-plane shear – See Figure

Metabolites – A substance formed in or necessary for metabolism.

Metamorphosis – The biology process by which an animal physically develops after birth or hatching, for example, when a larva develops to butterfly.

Metamorphosis inhibiting – To prevent metamorphosis from happening.

Mollusks/Molluscs – Animal strain with 85 000 species. Largest marine group of animal including 23 % of all know marine organisms. *Swedish: Blötdjur*.

Motile – A single cell organism with the ability of motion.

Mucus – Secret that are produced and covering the surface of mucous membranes. *Swedish: Slem/Slemhinna*.

Mutualistic gazing – Corresponding to a pair of snails that cleans each other's outer shells.

Noradrenaline Hormone – Hormone and neurotransmitter.

Organotin – Tin with hydrogen and carbon compounds.

Osmoregulation – The regulation of osmotic pressure of an organism in order to maintain the homeostasis, regulates the organism's water fluids from becoming to concentrated or diluted.

Out-of-plane shear – See Figure 21

Performance record – A record or list to track how something perform.

Riblets – Structure with many small ribs, similar to the rib structure in the body.

Secondary metabolites – see metabolites.

Sessile – Characteristics that indicate that the organism is immobile.

Sessile existence – the organism will stay sessile. See sessile.

Shear stress – See Figure

Shelled invertebrates – Invertebrates with shells. See invertebrates.

Tensile stress – See Figure 3

Tooth decay – dental caries.

Periphytic – Process in which an organism grows attached to a surface on a plant, algal or other substrate.

Photodegraded – The process in which a substrate is decomposed by light.

Planktonic – Primarily comprising microscopic algal and protozoa (from plankton).

Planktonic propagules – see propagules.

Plasticisers – Additive that changes the plasticity or fluidity of the material to which it is added. Are mostly used for plastics.

Polymer brush – Polymer layer attached with one end to the surface.

Predation – The interaction between a predator and its prey.

Propagules – A structure capable of producing a new plant; includes seeds, spores.

Protozoa – Group of unicellular eukaryotic organisms.

Recoatability – How well a coating can be applied on top of another coating.

Topology – The mathematical study of geometrical and spatial properties.

Transconductors – Converts voltage to current.

Volume to solid – Used about paint and indicates the paints true volume. This means the thickness of the dried film compare with the undried paint. For example, if the volume solid of a paint is 50 % it means that the thickness of the dried paint film is half the wet paint film.

Zoospores - A spore (part of the lifecycle) of an algal, fungi or protozoans, capable of swimming using a flagellum.

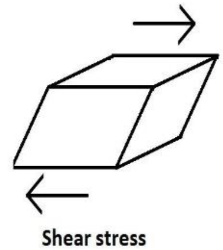

Figure 20 Illustrating shear stess.

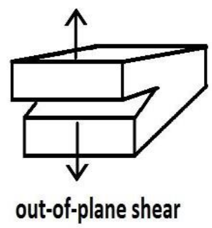

Figure 21 Illustrating out-of-plane shear.

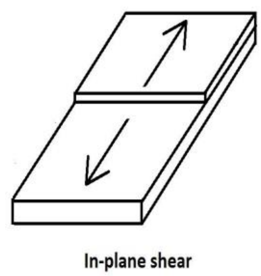

Figure 22 Illustrating in-plane shear.

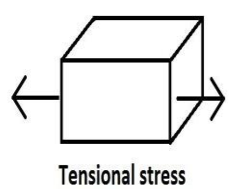

Figure 23 Illustrating tensional stess.

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